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Siting and Sizing of Embedded Generators
A Jamaican Network Analysis

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Siting and Sizing of Embedded Generators

A Jamaican Network Analysis

by

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Abstract

Increasing costs associated with fossil fuel generation and a recognition and acceptance of the finite nature of this resource, have partially contributed to the growing popularity of alternative energy generation technology. International environmental treaties have also forced many states, primarily developing states, to deliberately review their fuels use. Jamaica having such a challenge requires accurate information regarding the impact of integrating generation from such technologies into its existing network. However, given a lack of resources, little work has been done to gather the relevant data that is required to evaluate the impact of embedded generation. Instead the findings from networks in other jurisdictions that have different operational and technical characteristics have been utilized. Anecdotal information regarding the availability of satisfactory renewable resources and the minimal impact that certain levels of integration will have on the existing network abounds among the engineering community on Jamaica.

This research reviews the electricity and energy sectors of Jamaica. It further considers the efforts made by policy makers to fulfil the energy needs through a possible mix of fossil and renewable sources. Focus is then shifted to the analysis of available wind resource data which is then modelled to represent usable wind data for electricity generation. Actual system data is then used to produce an acceptable model of the current transmission network. The operation of the network is then considered on varying generation and loading conditions both with and without the inclusion of renewable sources. A final assessment of the impact of such sources is then made based on the magnitude and location in the network.

The study concludes by highlighting the benefits to be derived from this work and reviews the challenges faced while conducting the study. It also recommends ways in which improvements to the system can be realized.

Acknowledgement

It is with immense ease that I thank Dr. Li who in her own way has encouraged self learning and discipline during the period leading up the production of this thesis.

My family continues to be a tower of strength to me during this period, as they have allowed me to be away from home for long periods in an effort to complete my work. Thanks also to my church family who continue to lend support through words of encouragement.

I must covey my appreciation to the company representatives from the various Jamaican entities that have facilitated my gathering of information. Specific mention must be made of those from the Jamaica Public Service, West Indies Aluminium Company, The Meteorological Office of Jamaica and the Petroleum Corporation of Jamaica. Thanks also to my superiors at the University of Technology, Jamaica, who have supported me being off duty for extended periods.

Finally, appreciation must be expressed to the other members of this research group who have made me feel welcome. Thanks too to Drs. Miranda and Kuri who challenged me to use some of the tools which eventually helped in my understanding of the research topic.

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CHAPTER 1

Introduction

Chapter one provides a synopsis and a rationale for the study. It highlights the motivation for the study which includes the need for the country to establish financial and environmental benefits of using renewable energy in the Jamaican network. This chapter also posits the objectives for the study and a number of the challenges that are present and may arise. Whilst highlighting the challenges, a balanced view is also necessary, therefore the chapter also seeks to identify a number of benefits that renewable energy affords the Jamaican society. The layout of the thesis is also presented. it is broken into three sections: First it looks at the existing Jamaican electricity sector; secondly it posits the use of renewable technologies; and finally it considers the impact of the results and the conclusions that can be garnered from them.

Countries within the Caribbean region have long been seen as pristine and unspoiled. For many individuals, they represent the perfect getaway from the fog and smog of more industrialised nations. While continuing to market their natural beauty, climate and charm, many other fundamentals have either been ignored or given scant regard. As populations grew, the need for industrial and developmental changes to meet the changing demands also grew. To this end, practices that were once the “fiefdom” of the industrialised nations became common place in these territories. Among these practices is the use of fossil fuels, in particular Oil and Diesel, in electricity production.

Jamaica, like its Caribbean neighbours, established and expanded the use of Oil and Diesel in electricity generation to the point where it now represents approximately ninety five percent (95%) of the country’s total installed generation capacity (Jamaica Public Service). Like their industrial neighbours, countries within the Caribbean have had to face the reality of this unsustainable way of life. Although this reality has been recognised, the age old attempts by successive Jamaican governments to find oil from on and off shore sources remain a priority. Until this “find” is realised the country is faced with erratic economic fortunes which are inextricably linked to international fluctuations in the price of oil.

Some major economies have sought to meet their energy needs through other fossil fuels such as coal; Jamaica however cannot afford to simply shift from an over reliance on one fuel source to the next. Such an approach would result in the inevitable crunch that will emanate from the expected economic law of demand and supply being applied to coal. It is for this, among other reasons, that the need for diversification in energy sources arises, and in particular from sustainable sources.

With the agreements such as the Kyoto Protocol and the millennium development goals, the country has established national objectives regarding the diversification of energy sources for electricity generation. While these objectives are plausible, they must be grounded in clear scientific data. Simply acknowledging the integration of electricity from alternative sources in other jurisdiction cannot be used as the basis for providing policy direction for the country. Such policy must be based on relevant study/studies being conducted on the network.

This research therefore seeks to identify the level of diversification that is possible from two of the more mature alternative technologies that now exist on the Island. This diversification is based on sustainability, the environment, cost and general technical requirements.

Assessment of these measures is made with due consideration for the peculiarities of market structure, pricing mechanisms and technical operations of the Jamaican system.

The primary solution being put forward, by this researcher, is the expanded use of embedded, wind and hydro generation systems. Embedded Generators (EG) or Distributed Generators (DG), by definition, are generators connected to a distribution network, as opposed to a transmission system. With the changing energy needs, this definition has been expanded to include generation inserted in any existing network (Nick Jenkins, 2000). To this extent varying challenges, financial and technical, are presented when such generation is connected at either the transmission or distribution levels. These challenges can however be met by considering the benefits that can accrue from commercial activity and regulation.

With the inclusion of EGs, power flow can emanate from both the high and low voltage levels, thereby making the network active [1]. To facilitate this change in operation, consideration must be given to the manner in which such generation interfaces with the existing network as well as the capacity of the existing plant to carry the additional power flow. In addition to changes in the system capacity, consideration must be given to the variability of some DG (Wind) as well as the seasonal unavailability of water.

1.1 The Jamaican Economic Challenge

The mainstays of the Jamaican economy, for foreign exchange earnings, have been Mining, Tourism and Remittances. The global economic challenges, since 2007, have brought into sharper focus the need to further diversify the economic base of the country. Earnings from remittances and mining fell by more than fifty (50) percent, forcing the government to seek financial support from the IMF for balance of trade payments. Manufacturing, which is the plank on which many industrialised economies have developed, produced only eight (8) percent of the country's total gross domestic product (GDP) in 2008. In the neighbouring country of Trinidad and Tobago, manufacturing accounts for close to forty (40) percent of GDP.

One of the differences between both islands is the cost of electricity. The cost of energy to manufacturers in both countries is shown in the table 1.1.

As a key component to the manufacturing cost, the significant disparity in the demand charge provides some justification of the differences in contribution of this sector to the economies of both countries.

The differences in electricity cost are due in part, primarily to the types of fuels use in its generation. All of the electricity in Trinidad and Tobago is produced using natural gas. In Jamaica however, approximately ninety-five percent (95%) is produced using heavy fuel oil and its derivatives. Consequent to this is the fact that weekly variations in the cost of oil is factored into the final monthly bill, thereby making electricity cost a significant variable in final product costs.

Table 1.1: Energy and demand Charges for Industrial Customers in Jamaica and Trinidad and Tobago

	Energy Charge per kWh ($US)	**Minimum Demand Charge per kVA ($US)**	**Maximum Demand Charge per kVA ($US)**
Trinidad and Tobago	0.023 to 0.034	5.78	7.81
Jamaica[1]	0.036	12.53	13.92

[2] [3]

With the increasing costs associated with fossil fuel generation and an acknowledgement of its finiteness, the popularity of alternative energy sources is now greater than ever. Countries within the Caribbean region, with the exception of Trinidad and Tobago, are all dependent on imports of fossil fuels for electricity generation. However many of these countries are rich in natural resources that can provide a significant portion of their energy needs in a sustainable way. Geothermal, Solar, Hydro and Wind are but four of the technologies that these countries possess. While targets have been set for the use and increased exploitation of these resources, the relevant mechanisms to facilitate such expansions are in need of revision and or creation.

Jamaica's original name of "Xaymaca", land of wood and water, highlights in part one of the great resources of the island. Its geography of mountainous interior and flat coastal areas

[1] These charges are in addition to cost for fuel and Independent Power Producers

produces “natural” “wind tunnels”. The existence of these resources makes it therefore important to explore what benefit, if any, they can provide in achieving the goal of a sustainable and affordable electricity supply.

Vestiges of the country’s colonial past in the form of Sugar production produces Bagasse which can also be used in electricity production. Its location in the western Caribbean while making the country susceptible to hurricanes, owing to its warm waters, also makes the potential for Ocean Thermal Energy Conversion (OTEC) another generation possibility. The yearlong tropical climate makes the Island a prime candidate for greater use of solar power. And the list of possibilities could be extended even further. However the key objective is highlighting the fact that with its struggle to produce electricity from imported fuel the country remains rich in natural resources. How well then can these available resources be used to facilitate the economic activities such as Tourism through the provision of more reasonable electricity without impacting the quality of supply.

1.2 Energy Use by Sector

Ninety percent (90%) of the country’s energy needs is supplied through the use of imported petroleum products [4]. A breakdown of the main activities supported by this fuel source is shown below.

Twenty two to twenty five percent of all the petroleum products have been used for electricity production between 2003 and 2008. However, this figure represents only the electricity produced by the public electricity supplier. Some major manufacturing/mining companies actually produce their own electricity as a means of hedging against a somewhat costly and unreliable public supply. Although the distinction is not shown in this data, sectors such as tourism rely heavily on appropriately priced electrical energy. This dependence does not only exist through its direct operation but also through inputs from light manufacturers such as food processors, who themselves become uncompetitive, owing to the cost of electricity. This type of interconnection between activities highlights the vicious circle developed through almost total dependence on this imported fuel source.

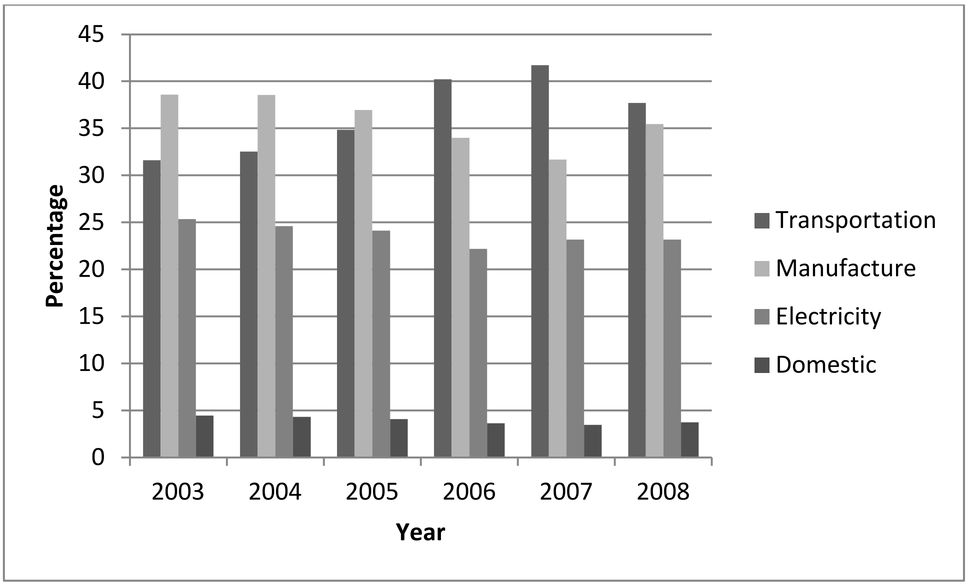

Figure 1.1: Percentage Use of Petroleum Products per Major Activity for the Period 2003 to 2008

[5]

Transportation, inclusive of road, rail, aviation and shipping, accounts for a significant portion of the imported fuel. Notwithstanding global efforts in reducing the use of fossil fuel for road and rail transportation, through the use of electricity, a similar approach becomes redundant in the Jamaican economy given that the electricity is produced primarily from costly, polluting petroleum.

The manufacturing sector is the second largest consumer of the imported commodity. Unfortunately much of this consumption is also used in electricity production.

Household consumption is based in large measure on cooking, through the use of liquid petroleum gas (LPG). This consumption could be reduced should a competitively price of electricity is provided.

1.3 Research Motivation

During the oil crisis of the 1970s many nations, including those in the Caribbean, looked to alternatives in meeting their energy requirements. To this end, Jamaica started research in solar technology (primarily for water heating) as well as invited outside interest to continue oil explorations across the island. During the eighties three additional hydro plants were installed, biomass was identified as a potential source to further offset the impact of these higher prices. Ocean Thermal Energy Conversion (OTEC) was also identified as a possibility, given the vast potential identified in the Caribbean region. Incentives for using renewables (primarily for heating) were also made available.

However as international oil prices fell, national efforts in finding alternatives to the product waned. Import restriction once placed on the importation of motor vehicles were lifted which helped to dramatically increase oil consumption across the island. The change in policy helped to push the country's oil bill beyond the one billion dollar mark in 2005. The fall in price also 'facilitated' the public electricity company in acquiring diesel fuelled generating plants to meet some of its base load demand.

A decade later, the price of oil once again increased dramatically over 1980s levels and once again the same methods once adopted in the late seventies are repeated in exact fashion; with the exception of hydro electricity which had the last plant installed in 1989.

The sharp increases in oil prices so far in the twenty first century are not, for the most part, the result of conflicts between nations or demand but rather a result of market speculation/activity, according to some analysts. Whatever the true reasons, these price movements is the clearest indication that countries can no longer "sit back" and wait for the commodity to return to acceptable price levels. To this end, it is necessary to find a permanent solution for economies such as Jamaica's. It is therefore necessary to consider and evaluate what may be, if any, the impact of these solutions.

Though the reasons for high world oil prices have changed, the impact on the country's economy remains the same. The product having reached pricing levels "which was at one time the product of active imaginations" have settled at a point that still remains a matter of concern to an economy that needs to expand. Coupled with its ill effect of increasing the production of green house gases, a meaningful reduction in the use of petroleum products in at least one economic activity, was worthy of exploration.

This researcher was therefore interested in assessing the impact of using some of the natural resources already identified, in helping to solve this challenge. In making initial attempts of looking at the solutions being put forward by the responsible state agencies there was an absence of data that were wholly relevant to the island's power system network. There was also the absence of an efficient system model available to the academic community for deeper analysis.

The Jamaican government having sought to highlight the possibilities associated with renewable energy by investing in wind generation, failed to provide either a clear policy regarding the Renewable Energy Source (RES) technology or a supportive operating environment to facilitate its expansion. This study is therefore geared towards the establishment of the technical framework that will help to drive the relevant policies for the use of Electrical Renewable Energy Source (RES-E) in the Jamaican electrical network.

It is therefore for these reasons that I believe this research is necessary.

1.4 Research Objectives

The objective of this research is to establish the benefit of using embedded generation in helping to satisfy the electricity demands of the island. Notwithstanding the use of some stochastic data, assessment will be made based on a conventional deterministic methodology. The electricity market on the island is monopolised in transmission and distribution. While competition exists in generation, expansion in this area is limited to the provisions of a Least Cost Expansion plan. This plan, on the surface is deleterious to expansion through the use of high capital cost technologies such as wind. Notwithstanding the fact that the cost, capital and operation, of wind has fallen significantly since the turn of the century makes this research plausible. The aims of this research are:

1. Establish a robust computer model of the entire existing transmission network

2. Demonstrate the impact on the network resulting from increased annual load demands.

3. Demonstrate the impact of using wind, at previously identified sites, on the network

4. Establish the best siting of wind farms within the network from the sites identified

5. Establish the financial and environmental benefit of using renewable energy in the Jamaican network.

6. Provide the basis for the establishment of a policy framework for the use of embedded generation in the network.

1.5 Research Contribution

Jamaica is an island with vast human potential. Its exotic food and fruits are known worldwide. Much of the value added benefits of these products are derived by other countries with more affordable sources of energy. Transformation of the economy will find its root in the availability of affordable and sustainable energy.

Expansion in the electrical generation capacity, and at a better price than is now being offered, will require significant investment. Such investment will come primarily from private capital, whether as generator or financier. Such capital would find greater security in knowing that there is a clear and unequivocal policy framework governing investment in this area. For a policy document to be sustainable, it must have its roots in good research. I believe that this work will in part provide, in part, the basis for the strengthening of the policy framework which governs both the use of renewable energy generation and generation expansion. The main contributions of this work will therefore include:

1. Assisting policy makers to clearly articulate the areas within the country where the placement of embedded generation systems would be best suited. This will be based on whether such considerations are for environmental or technical reasons. Additionally, information will be provided to guide the size of the systems used within the network at the prescribed areas.

2. Further enhance the ability of private individuals or companies considering potential investment in the electricity generation sector to have a means of independently assessing the impact of such connection would have on the network.

3. Make available within the academic community, for the first time, a robust model of the Jamaican Power Transmission Network. The network will be established such that expansion in any aspect of power system operation, namely generation and transmission can be modified and assessed. This flexibility will open an entirely uncharted frontier for the bright minds of the engineering community, within academia, to concretely conduct meaningful research work associated with Jamaica.

Notwithstanding that the main thrust of this work is the use of wind resource, the exploration of all renewable technologies will be made possible, for the local network. All considered the work to be undertaken will provide for better and more technical solutions to the challenges facing the Jamaican electricity network.

1.6 Thesis Structure

The thesis consists of eleven chapters.

Chapter one provides an introduction to the relevance of the work considered as well as the source of motivation responsible for its undertaking.

Chapter two looks at the electricity sector in Jamaica. Consideration is given the operational as well as the market structure on the Island. There is also a brief comparison between the current structure and that of another liberalized market.

Chapter three reviews the existing challenges associated with the use of renewable energy, primarily for electricity generation, in Jamaica and wider Caribbean region. Focus is also placed on the schemes adopted by other nations to increase the use of the technology within both their electricity and general energy mix. The chapter also highlight the challenges and considerations necessary for the integration of renewable, primarily wind, energy into existing networks.

Chapters four through six provides details regarding the methodologies, inclusive of tools, used in creating the system model used, with respect to generation, transmission and load. The chapter also sets out the bases on which the various analyses are done in reaching the various conclusions of the study. In addition to the system model the chapter also looks at the wind simulation models as well as greenhouse gas production.

Chapters seven through ten contains results associated with the main areas analyzed, inter-alia, operating characteristics, impact of siting and sizing on these characteristics as well as green house gas production.

Chapter eleven summarizes the conclusions to be drawn from the study, the recommendations emanating and for further work as well as the limitations associated with the study.

CHAPTER 2

The Jamaican Electrical Energy Sector

Chapter two provides an in-depth view of the Jamaican electrical energy sector. It considers and highlights the provisions of the last two Jamaican Energy policies in relation to the renewable energy use in electricity generation. Additionally, consideration is given to the alternatives to oil and its derivatives. These alternatives include coal, liquefied natural gas, wind and cogeneration systems. The alternatives are explored and the limitations for their use highlighted. The chapter concludes by reviewing the operational features of the network.

"***Insanity is doing the same thing over and over again and expecting different results***" (Albert Einstein); these words are true for individuals and nations and aptly describe the effort by the Jamaican government in its quest to solve the nation's energy crises. Jamaica like many developing nations is heavily dependent on crude oil and its derivatives for electricity production. To this extent increases in the price of oil has a direct impact on the costs of production and by extension the cost of living.

Within the last forty years the response by successive governments to sharp, sustained increases in the price of oil has been the same. Among their response is to have increased onshore as well as offshore oil exploration of the island. Should they one day disprove Einstein's insanity theory and find the commodity, the need to identify alternative, sustainable solutions would still remain.

It is therefore necessary to look at just how and where within the economy oil and its derivatives are consumed. Reviewing the current policy regarding current and future activities towards its consumption is also of critical importance.

The options available for the production of electricity is also of critical importance to fully establish how best to move forward.

2.1 The Jamaica Energy Policy

The revised version of the 2006 Jamaica Energy Policy[2] highlights some ten (10) key objectives. Those objectives relevant to this study are:

1. *An energy sector that provides affordable energy supplies to all consumers throughout Jamaica with the capacity to meet long-term growth in demand; and one that contributes to the international competitiveness of the productive sectors of the economy*

2. *An energy sector that is focused on the modernization and expansion of the energy infrastructure (e.g. generation, transmission and distribution systems) to ensure safety, affordability, reliability and competitive advantage*

[2] Revised in 2009 and renamed Jamaica Energy Policy 2009-2030

3. *An energy sector that is driven by private sector investment within a policy and regulatory framework that fosters investments, competition, efficiency, a level playing field and transparency*

4. *An energy sector that is environmentally sustainable with significantly increased use of economically viable renewable energy sources*

The key features of the 2006 document had as part of the overall strategy to:

1. *Establish a market based pricing mechanism for electricity*

2. *Increase the overall use of electricity from renewable sources to fifteen (15) percent of total demand by the year 2012.*

3. *Establish processes for the:*
   i. *procurement of systems using renewable technology*
   ii. *incorporation of renewables within the electricity network*

4. *Institute the diversification of fuel sources to include coal and natural gas.*

5. *Completion of a least cost electricity expansion plan*

Though four years apart, both documents have generally pointed in the same direction towards finding a solution to the country's energy needs. Notwithstanding this the technical framework towards facilitating the implementation of any of these or other strategies must be created; which this research proposes to do. One positive change is highlighted in items 4 and 5 of the respective documents; originally a least cost plan would have proven inimical to the establishment of renewable energy facility, however the redrafted document has been written in recognition of the now competitive prices among all available technologies. This recognition provides greater impetus to the need for this research.

2.2 Current Objectives in Renewable Energy Use

2.2.1 Wind Energy

As a direct result of the mandate set in the Jamaica Energy Sector Policy, the Petroleum Corporation of Jamaica began operation of the first commercial wind generating facility on the island (Petroleum Corporation of Jamaica). With an installed capacity of approximately twenty one Megawatts (21 MW), the wind farm provides on average, 1.3% of the country's total demand, based on its average output.
Among the stated objectives, this project is expected to:

1. Diversify the Nation's energy mix
2. Utilize indigenous (sustainable) energy resources
3. Reduce imports of petroleum
4. Reduce emission of green house gases
5. Provide testament of the country being a signatory to the United Nations Framework Convention on Climate Change (UNFCC)

2.2.1.1 Diversification of Sources

With the inclusion of Wind generation, the energy mix of the country has now expanded to include Fuel Oil, Hydro and Wind; to this extent the objective regarding diversification has been met. However given the current level of penetration it may be argued that this diversification is without significance. At the end of 2005 the total installed public electricity generation capacity was seven hundred and seventy five megawatts (775 MW) of which wind accounts for 2.7% [4]. At over eight hundred megawatts (800 MW) in 2008 and the total wind capacity unchanged, the percentage has declined further. The percentage input from wind will increase as the farm is currently being expanded by a further eighteen MW at a cost of US$18.

The Jamaica Public Service Company has started work on two new renewable power projects in 2010 as part of its strategy to gradually reduce dependence on oil for electricity generation [6].

These projects will result in the addition of over 9 megawatts (MW) of new generating capacity using hydro and wind power. The two projects are: a 6.3-megawatt hydroelectricity power plant in Maggotty, St Elizabeth, and a 3-megawatt wind farm in Munro, St Elizabeth. The new hydro project will see the expansion of the existing hydroelectricity plant in Maggotty. This plant now accounts for close to 30 percent of the 21 MW of installed hydropower owned by JPS. The wind farm, on the other hand, will be the first wind project to be implemented by JPS. The 3-megawatt turbine is being built as a pilot, with plans for future expansion. Both projects are expected to cost an estimated US$38.7 million.

2.2.1.2 Utilization of Indigenous Energy Sources

Coupled with Hydro-Power; electricity generation from indigenous sources accounts for 5.3% of the total installed capacity. Seventy five percent (75%) of the installed hydro-capacity are connected as ‘run of the river systems’, thus being totally dependent on rainfall levels across the country. It is also important to note that the last hydro plant was installed in 1988 [7].

While national targets have been set to increase the percentage of energy from renewables, there have been no clearly established and articulated incentives to encourage growth in this area. The renewable target, for Jamaica, of fifteen percent (15%) by 2012 is similar to that set by the UK earlier in the decade. However, as outlined chapter 3, the UK has developed strategies to ensure that such a target is met. Currently the single wind farm project was established by the Government in conjunction with the Government of the Netherlands. However if growth is to be seen in this area then it must be led by private sector interests; this will occur only when they can clearly identify potential profits. Notwithstanding invitation of interest during the last three years for private investment for the expansion of the wind farm; it has been the government that has finally undertaken to expand the facility by a further 18 MW [4]. While companies and some individuals have taken it upon themselves to use renewable energy, there is only now the development of direct incentives for its use as set out in the 2010 -2030 energy policy.

The new policy document has also revised the renewable energy targets 2012 to 2030 as shown in the table below.

Table 2.1: Jamaica's Renewable Energy Targets

Year	2008	2012	2015	2030
Target	5.60%	11%	12.50%	20%

2.2.1.3 Reduced Petroleum Imports

Based on total electricity produced in 2004, the total barrel of oil equivalent (BOE) for hydro and wind electricity averaged Eighty Three Thousand (83,000) and Twenty Thousand (20,000) respectively. In 2008 these figures stood at Ninety Eight Thousand (98,000)and Thirty One Thousand (31,000) BOE. As a percentage of the total amount of oil used, hydro and wind represented a mere Two percent (2%). [8]. Based on this trend it would not be prudent to consider these technologies as having the desired effect of meaningfully reducing oil imports. However as part of the overall mix of fuels, including LNG and coal, to be implemented, this desired goal seems quite feasible.

2.2.1.4 Impact on Climate Change

Wind energy is renewable and clean, and as such lends itself to a reduction in the production of greenhouse gasses (GHG). GHG are gases that absorb and emit radiation within the thermal infrared range. The main pollutants emanating from oil and diesel powered plants are Carbon Dioxide, Nitrous Oxide, Sulphur Dioxide and Mercury. While the production of these pollutants remains proprietary[3] information of the utility company, the reduction in the use of oil owing to electricity production from wind is a good indicator of a positive impact on climate change.

The wind farm by virtue of its contribution to the reduction of such gases, sold Certified Emission Reduction certificates, under the “Kyoto Protocol Clean Development Mechanism” (Jamaica - Wigton) to the Netherlands; thereby providing another source of income for potential investors.

[3] Emission information logged with the National Environmental Planning Agency (NEPA) is partially available via access to information request.

2.2.2 National Wind Proposal

“*The results of a number of studies (Tande & Hansen, 1991) indicate that there are optimum levels of wind power that can be contributed to a system beyond which problems can be created. Therefore, the quantity of wind power that can optimally be put into the total electricity production system will be limited; especially if no storage capacity is available. Specific characteristics of the utility systems will allow the optimum input of wind energy to range from a low of* ***10 per cent to, in special circumstances, a high of 50 per cent*** *(Turkenburg, 1992). It is reasonable to conclude that where wind power input is less than 10 percent of total electricity production, no significant problems should occur. This 10 percent level of penetration should cause no practical economic disadvantage to accompany the growth of wind power in any country over the next 30 years because potential wind resources normally fall within the range of 8-10 per cent of a country's energy output*”.

This is a quote from the former managing director of the PCJ in his book published in 1996 (Wright, 1996). At the time of publication however, the “resurgent” wind energy was still in its early stages of development. The technologies having evolved, now facilitates the manufacture and installation of wind turbines capable of producing outputs of 4.5 MW for offshore operations (Vestas). Improvements have also occurred in the power electronic interface between generators and the network. It should also be noted that the persons quoted by the author, conducted their research, primarily in the Netherlands and other parts of Europe; where the transmission and distribution networks are much more robust than that on Jamaica.

The European Wind Energy 2005 publication states that “*It is considered that wind energy can meet up to twenty percent (20%) of electricity demand on a* ***large*** *electricity network without posing any serious technical or practical problems*”

While this maximum level of penetration is less than that referred to by the former PCJ head, it is qualified by the use of “large” electricity network. It therefore is necessary for one to determine if the Jamaican network is “large” enough and by extension what level of, and where such, penetration can be accommodated. Further qualification of both statements is necessary as Denmark was possibly the only country that had twenty percent (20%) of its electricity demand, in some areas, supplied through wind in 2005 (European Wind Energy Association). Notwithstanding the fact that the level fell to approximately 15% in 2006, the penetration, increased again to 20% the following year and has remained constant thereafter, according to data from the Danish Wind Industry Association. Also from data provided by the European Wind Energy Association (EWEA), Denmark and Germany are the only two countries which have wind energy of more than ten percent (10%) of the total energy consumed in 2005 [9].

With the establishment of the Wigton Wind Farm on the Island through a joint effort between the Governments of Jamaica and the Netherlands interest has now grown into the possibilities of wind being a crucial part of the electricity market. The Farm is being pointed to as the perfect model for what can be accomplished in wind energy. However, while returns may be reasonable it is necessary to fully assess from an academic standpoint:

1. The true cost of the wind farm and that associated with further investments in similar farms given that:

    a. A major grant was received by the PCJ, from the Netherlands government to purchase the wind turbines for the project and

    b. Full connection costs were not met by the current owners of the wind farm.

2. How expansion in wind energy, and other EG, will affect the current system

3. What considerations were and will be required to establish connection with the national grid, given that currently there are no established procedures governing such an arrangement.

4. How will wind farms benefit the current network with respect to operation costs

2.2.3 The Wigton Farm

In 2003 ninety seven percent (97%) of all the electricity produced on the island came from fossil fuel. Following the commissioning of the first commercial wind facility in 2004 this figure was reduced by a mere 1%.

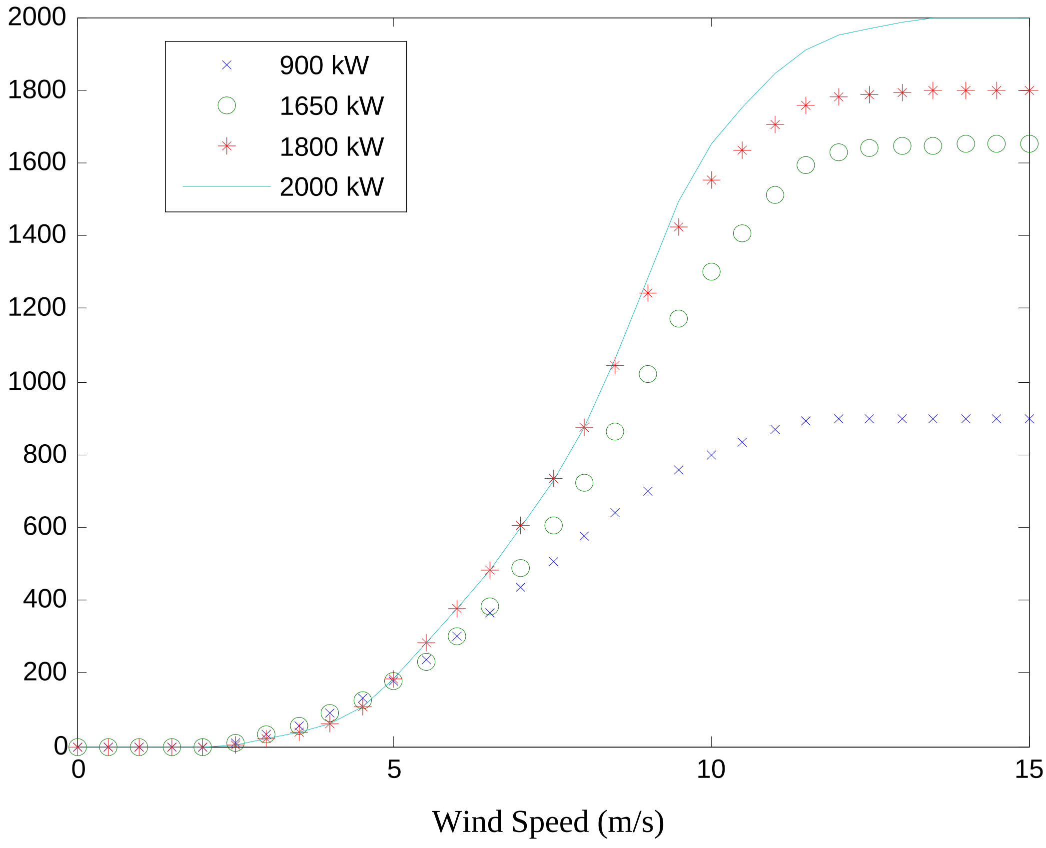

Figure2.1: Output power curves for wind turbines of varying capacity with respect to wind speed

[10]

The farm consists of twenty three generators, each having a capacity of nine hundred (900) MW, providing a total installed capacity of 20.7 MW. The average wind speed at the site is 8.3 m/s. For the output curves shown above the average power output at this wind speed is shown in table 2.2

A superficial analysis of these figures shows that given the improvement in technology the output power for a similar average input wind, results in increased output. Comparing the generators at Wigton with that having a maximum output of eighteen hundred (1800) MW, it shows an increased output of approximately fifty percent (50%).

Table 2.2: Estimated Turbine Output at Average Wind Speed at Wigton

Maximum Turbine Output (kW)	900	1650	1800	2000
Average Output at 8.3 m/s (kW)	612	804	971	979

It is for this reason that the capital and operation costs must be assessed with respect to the expansion of the current facility and the establishment of others.

2.3 Alternative Solutions to Oil Use in Electricity Production

It is without doubt that a sustainable economic forecast for the country will be heavily dependent on having an affordable, continuous source of electrical energy. Given this requirement the government has turned its attention to the JPSCo, the Petroleum Corporation of Jamaica (PCJ) and the Energy Ministry for solutions.

As part of achieving this intended goal, the 2006 energy policy identifies the use of the following as part of the future energy mix:

1. Introduction of Liquefied Natural Gas (LNG)
2. The use of coal
3. Expansion in cogeneration systems
4. Expansion in the use of wind generated electricity

The 2010-2030 policy however identifies the use of LNG as the key medium term strategy for energy diversification. The new policy also identifies increased renewable energy use; however, coal and cogeneration have been replaced as main areas of focus by Nuclear energy.

2.3.1 Liquefied Natural Gas

At the time of developing the 2006 policy, the idea to consider LNG as a viable option for an economy such as Jamaica was suspect at best. This was due to the gradual increases in the price of the commodity, seemingly tracking similar increases in the price of oil, thereby hobbling the expected potential benefit.

American market prices, on which Jamaica depends, recorded average increases in the price of natural gas of sixty eight percent (68%) over the period 2000 to 2004; concomitantly crude oil varied from an average of Twenty Seven Dollars to a high of Forty Five Dollars, representing a Sixty Six percent (66%) change. (Institute of America)

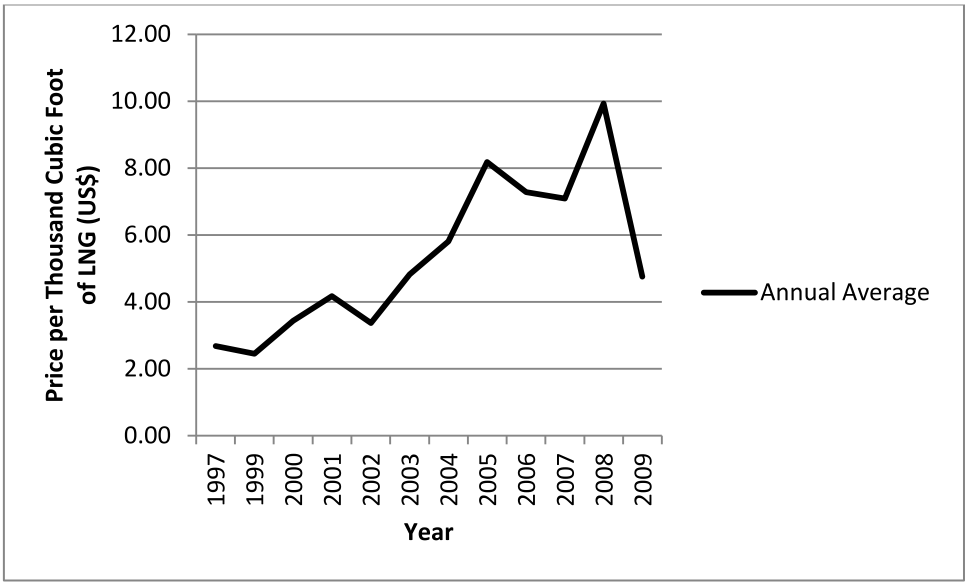

Figure 2.2: Average Annual LNG Prices on the US Market between 1997 and 2009

[11]

While the tracking of prices between the two continued up to 2008; LNG prices have tapered downwards and have remained stable, the price of oil on the other hand having moved downwards have climbed steadily back towards 2007 levels.

Given the current outlook for LNG and the growing maturity of the market, the focus on it as an alternative can now be considered as a feasible option to oil. Current efforts in identifying a long term supplier will prove beneficial. Should this plan eventually materialise, it will provide a respite for the economy, however it does not deal with the question of long term availability of the commodity and the need to reduce green house gases.

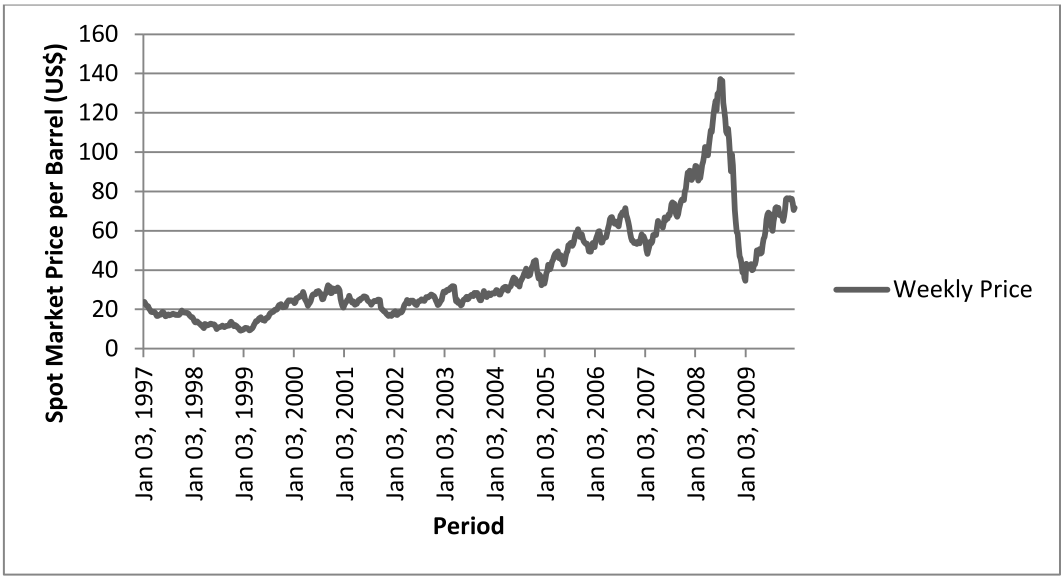

Figure 2.3: Weekly All Countries Spot Market Oil Prices Weighted by Estimated Export Volume between 1997 and 2009

[12]

To prepare the island for the use of natural gas the government through its agencies and the utility provider have begun a programme of retrofitting some plants. In the bauxite sector where together with the Aluminium Company of America (ALCOA), the government is undertaking a massive expansion programme; as part of this programme new generation plants are being installed which are capable of using natural gas. [13]

The expansion project while ongoing is yet to finalize power purchase agreements with the JPSCo. The issue is further compounded by the fact that the ALCOA plant will be a “must run” plant and hence not subject to economic dispatch. This retrofitting and new installation would be done with a view of the future.

2.3.2 Coal

In the mid 1990s the use of coal supplied approximately fifty percent (50%) of the energy produced in the United Kingdom [14]. At the same time Gas accounted for fifteen percent (15%) of the total. However by the end of the century, the balance shifted with coal and gas accounting for thirty two percent (32%) and thirty eight percent (38%) respectively.

Consumption figures for 2005 shows that there has been a decline in gas use and a corresponding increase in the use of coal. The resurgence of coal, accounting for thirty seven percent (37%), is due to both improvements in the technology, the lower cost of the fuel and a recognition that the heavy dependence on a dwindling supply of gas was not in the long term interest of the nation. While not replicated in exact proportions, the increase in coal use is seen in many other developed countries.

In light of these changes, it was only a matter of time before countries such as Jamaica, started looking at this fuel as a potential solution. This was also bolstered by the fact that the American company (MIRANT), which up to recently held controlling interest in the JPSCo, uses coal in several of its United States based operations. The government had therefore given the go-ahead for the company to establish a 120 MW coal based plant; which was scheduled to begin operation in 2008 [15] [16][4]

Coal may be a cheaper fuel source when compared with other conventional sources; however the construction of such plants is almost twice as expensive for establishing a conventional combined cycle diesel plant and thrice that of gas plants. Another major consideration is the fact that while economically coal may prove beneficial to the utility company, the country's reputation as a place of natural beauty may be tarnished. This would therefore ultimately affect the very services sector, mentioned earlier, that needs to be supported by cheaper energy. Like any other commodity coal suffers from the vagaries of supply and demand; figures for the period 2007 to 2009 show a movement in the price from an average low of Forty Dollars ($40) to a high of One Hundred and forty Dollars ($140) per ton.

The implementation of the 120 MW plant while solving the problem of having a "younger" base load plant, may create other issues as this single plant will supply in excess of 15% of the total demand as projected in 2012.

[4] The country's only previous foray into the use of coal was back in the 1980s when "out of frustration with the inadequacy of the public electricity supply" one major manufacturer used it for electricity production as well as for part of its manufacturing process. It is interesting to note that this company is once again exploring the use of coal to provide its heat and electricity needs. The fluctuation in approach further demonstrates the fact that attitudinal response to energy, on the Island, is reactive rather than proactive.

2.3.3 Cogeneration

Combined Heat and Power (CHP) also referred to as Cogeneration is a process in which an industrial facility simultaneously produces two or more useable forms of energy from the combustion of a single fuel source. While the technology is widely used worldwide, significant CHP use in Jamaica has been confined primarily to the bauxite and sugar industries. This was expanded to include at least one major food processor. Together with ALCOA, this manufacturer was supplying the national grid with a total of 23 MW. This has however ceased and ALCOA remains the only constant supplier of 6 MW to the national grid. With the expansion programme mentioned above, ALCOA's total production will increase to over 80 MW, predicated on the expected use of LNG. (The Jamaica Energy Policy, 2006 to 2020, 2005) Output from sugar manufacturers is based on the period during which they are in full production, given that their fuel source is primarily Bagasse which is a by-product of cane. This period spans approximately six months each year.
Given the improved efficiencies that can accrue from CHP systems, the government is seeking to encourage the participation of the other bauxite/alumina plants. The growing tourism market also improves the outlook for the potential of CHP systems from hotel facilities.

The definition here is confined to industrial facilities even though CHP systems range in magnitude from a few kilowatts to several megawatts. Micro-CHP systems are used mainly in temperate countries where space heating is required. With such use, the export capacity would be increased during the summer months. Against this background therefore, such systems would not warrant any significant consideration for Jamaica, outside of what has been mentioned above.

2.4 Electricity market Structure

The benefits of supplying power produced by any energy source are heavily dependent of the market in which they operate. For the purpose of assessing the benefits that have accrued and those that can be realised, a comparison of the UK market, deemed to be among the most liberalised worldwide, and that operating on Jamaica is outlined below**.** Notwithstanding that the UK has moved on from the electricity pool methodology, its use provides the opportunity to highlight just how far removed from an ideal market structure the is the Jamaican market. The "second generation" change from the vertical integrated model to the pool and to the now New Electricity Trading Arrangements (NETA) has driven competition, advancement in technology and better options for consumers. This is instructive as it provides the basis for the initial step that may need to be taken in moving towards competition to satisfy customer demands.

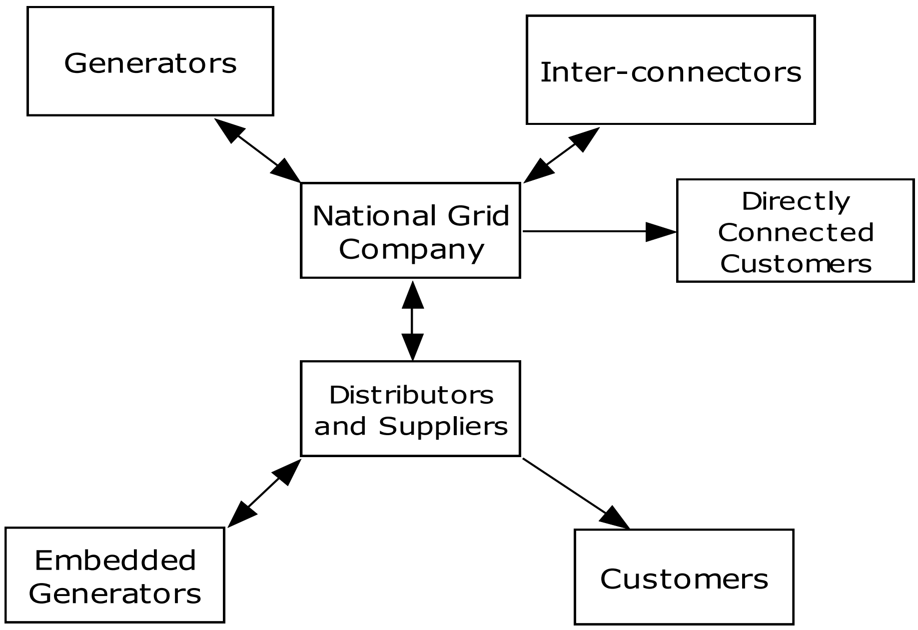

Figure 2.4: Power Flow in the UK Electricity Market

The figure above shows the power flow within the electricity market currently operating in the UK. Some key features are:

1. The suppliers is the entity responsible for contracting with the customer for the supply of electricity

2. Distribution network operators (DNOs) provide a fully maintained network for the passage of this power from the generator to the customer

3. The national grid company is ideally placed at the centre to balance the demand and supply between customers and generators.

4. Embedded generators may also be customers; however they are separated from that group based on their ability to supply power to the network. It is among this group that wind power generators currently operate.

5. Renewable obligation is applied to the system. By this suppliers are mandated to have a percentage of their energy supplied from a renewable source.

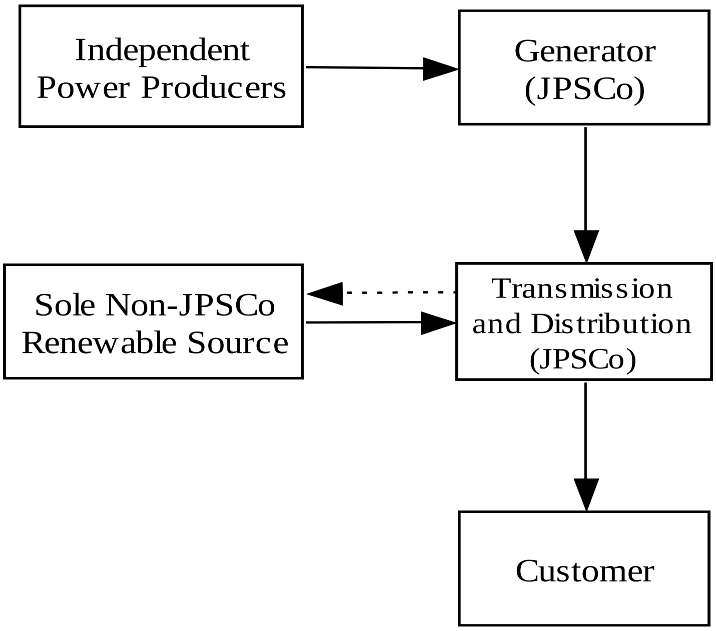

Figure 2.5: Power Flow in the Jamaican Electricity Market

Unlike the UK model, power flows within the Jamaican market is controlled by the public electricity company. Other inputs are from independent power producers (IPP) and the government owned Wigton wind farm.

While the license agreement between the government and the electricity company provides for the inclusion of private sector participation in electricity generation [17], there are no special incentives given to these generators. On the contrary, they are in direct competition with the JPSCo as a generator. The stark contrast with the UK market is that while a DNO cannot hold a supply license to enhance competition, the JPSCo is the primary arbiter of who supplies what and when.

The pricing mechanism used by the electricity company is known as “pass through pricing” [16]. Under this scheme the company is allowed to charge the consumer based on the fuel type that is used to produce electricity for the particular billing period. This fuel cost is separate and apart from the energy cost.

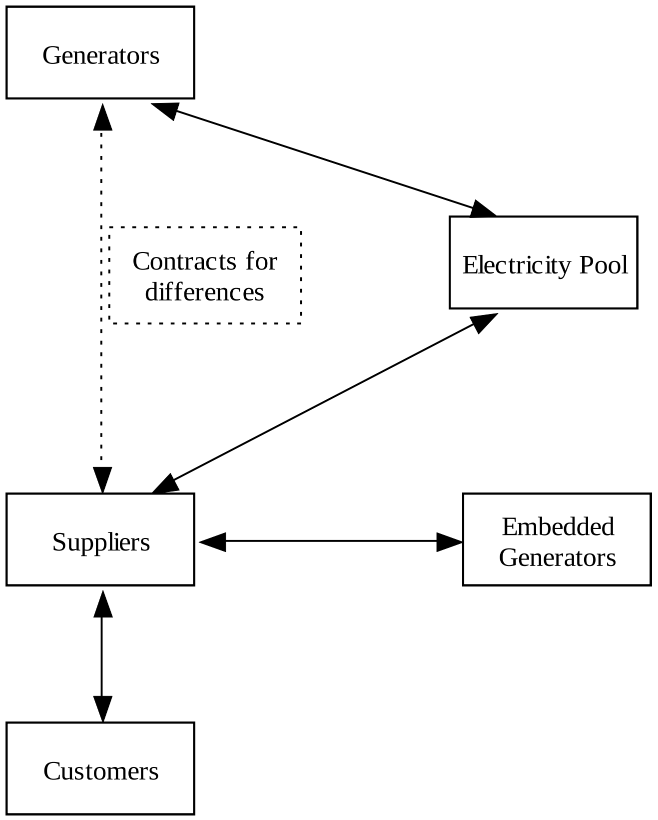

Figure 2.6: Contracts and Cash Flow in the UK Electricity Market

The contract and cash flow diagram highlights the competitive nature of the United Kingdom's market. Although the customer, like the Jamaican model, contracts with a single entity, the competition in the generator market ensures that they receive the best price.

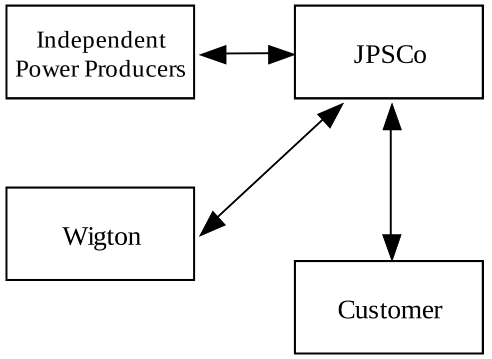

Figure 2.7: Contracts and Cash Flow in the Jamaican Electricity Market

Given the lack of incentives in the Jamaican market for renewables, the expansion in their use will be based on proof of its benefit to the network and the nation in general.

2.5 The Electricity Network Structure and Operation

The Jamaican electricity network is controlled by a fully integrated company, the Jamaica Public Service Company Limited, JPSCo. Except for generation, the JPSCo owns and operates the entire transmission and distribution network across the island. This exclusive license, issued in 2001, expires in 2021. Under its license, the company is prohibited from preventing any other entity or individual to generate electricity; however permission must be granted by the JPSCo for any excess generation to be exported to the network. [18]

Competition for generation officially began in 2004; however the JPSCo has been purchasing power from independent producers since the 1990s. Permission for the establishment of new commercial generating facilities is the purview of the Office of Utilities Regulation (OUR). [16] While this facilitates competition for the establishment of generation outside of the JPSCo, it is stymied by such generation being established under a least cost expansion plan (LCEP), developed by the JPSCo.

The most recent addition to the generation facilities on the Island is a 20.7 MW wind farm which is wholly owned by a government subsidiary. The facility operates with a load factor of approximately 35%, thereby providing the network with just over 7 MW. [19] Other planned sources of increased electricity input will emanate from expansion of one of the independent producers and sale of excess capacity to the JPSCo from the expansion of the mining operations of an Alumina company. [16]

2.5.1 Operating Voltages

The JPSCo operates with three main voltage levels. Transmission voltages are set at 138 and 69 kV. Distribution voltages have been standardised at 24 kV since the mid 1990s. There are still areas on the island however that continues to operate at distribution voltages of 13.8 and 6.9 kV. Power transmission is done via fifty three (53) substations of capacities up to 1GVA. Outside of the two main cities, Kingston and Montego Bay, which use cables, distribution is done via overhead lines. [7]

2.5.2 System Losses

System losses within the network have varied from a high of 22% to 16% between 1992 and 2002. [7] The most recent figures show that losses for the year 2006 were 22.9%. Just over fifty percent of the total losses are regarded as non-technical. These nontechnical losses result from theft.[5] Technical losses within the transmission section of network are the result of a combination of the relatively low transmission voltages and the significant distance between substations. The relative proximity of major load centres and generation facilities are shown in the generation map below.

2.5.3 Generation

The total installed generating capacity on the island is approximately 800 MW. This is supplied through a mixture of Wind, Hydro, Diesel, Oil fired steam and Oil based gas[6] turbines. The mix, as a percentage of the total installed, is figure 2.8.

The figure highlights the critical situation that exists on the island, where approximately 95% of the electricity produced is from oil and its derivatives. The sixteen (16) fossil fuel units of the JPSCo are sited in four plants, while the other ten (10) units belonging to the two independent power producers (IPPs), Jamaica Private Power Company (JPPC) and Jamaica Energy Partners (JEP), are sited in their individual plant facilities. The six plants are however confined to four geographic areas on the Island's south and north western coasts, shown on the map below. Plants situated at the Rockfort and Hunts Bay areas produce totals of 99 and 124 MW respectively. The Old Harbour facility produces 294 MW while at Bogue on the northwest coast a total of 224 MW is produced.

[5] This research will however focus on the technical losses.
[6] NB not natural gas

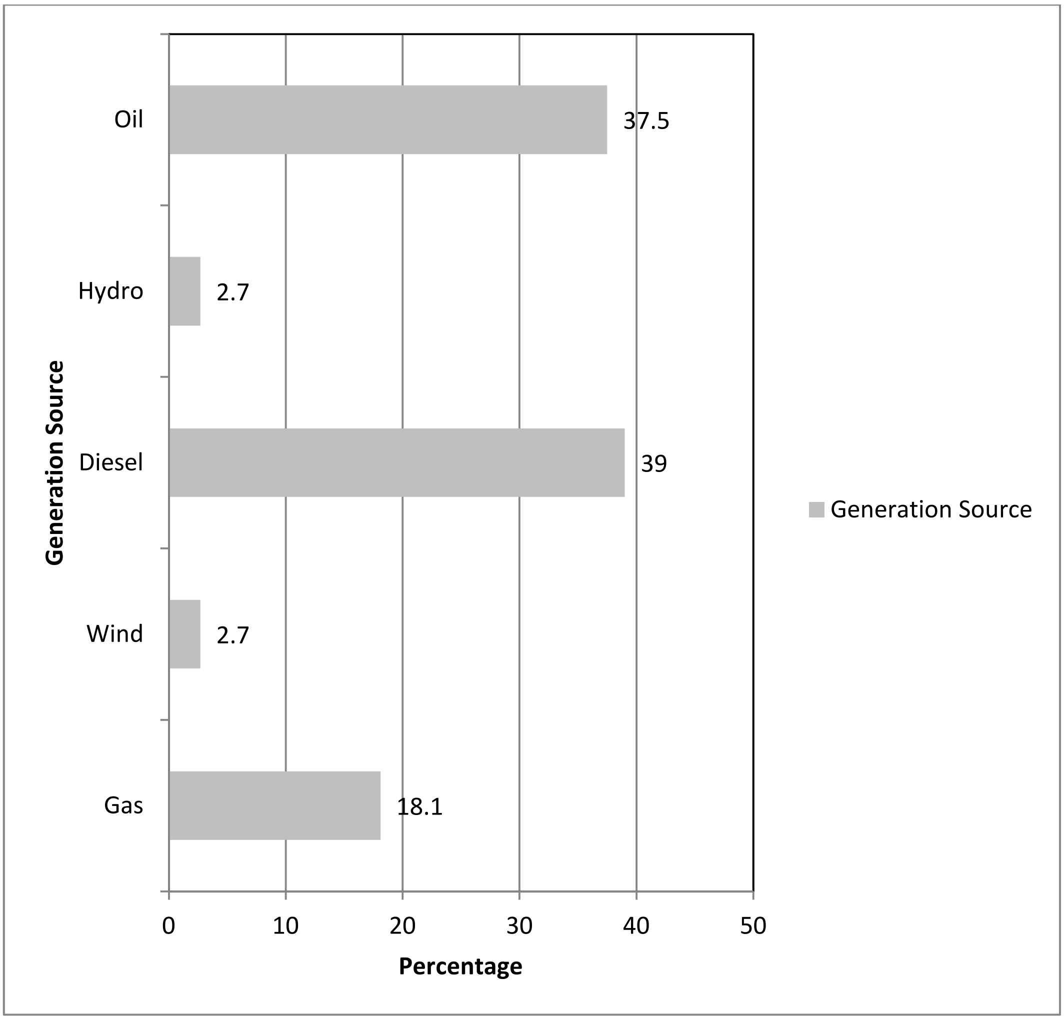

Figure 2.8: Fuel Type as a Percentage of Total Installed Generation Capacity, Developed from System Data Supplied by JPSCo

The eight (8) hydro electric plants scattered across the island are owned by the JPSCo. The plants which are all run-of-the-river units produce a total of 21 MW, which can only be considered as firm capacity during the rainy season. The lone wind farm is operated by a subsidiary of the government run Petroleum Corporation of Jamaica (PCJ). The facility consists of twenty three (23) 900 kW wind turbines, providing an installed capacity of 20.7 MW.

A further breakdown of the nearly 600 MW of installed capacity of the JPSCo consists of 290 MW of steam, 140 MW diesel, 140 MW gas and 20 MW hydro. The unit capacity/type, location and commissioning dates are highlighted in the table below. [7]

Figure 2.9: Geographical Location of Existing Generating Facilities

Table 2.3: JPSCo Owned Generating Plants Information

Generating Unit	Capacity (MW)	Plant Location	Commissioning date
Steam			
Units 1 to 4	30, 60, 65 & 65	Old Harbour	1967, 1968, 1970 & 1973
B6	69	Hunts Bay	1978
Diesel			
Combined cycle	129	Bogue	2004
Power Barge	40	Rockfort	1985
Gas			
GT 10 & 5	35 & 20	Hunts Bay	1974, 1993
GT 3 & 6-9	21, 18.5x3 & 30	Bogue	1972, 1990 & 1991
Hydro			
Upper White River	3.8	NA	1945
Lower White River	4.9	NA	1952
Roaring River	3.8	NA	1949
Rio Bueno	2.5	NA	1949
Maggoty Falls	6.3	NA	1966
Constant Spring	0.8	NA	1989
Rams Horn	0.6	NA	1989
Rio Bueno "B"	1.1	NA	1989

[7]

The remaining generation supplied by the IPPs is broken down as shown in the table below.

Table 2.4: Independent Power Producers Generating Plant Information

Producer	**Capacity (MW)**	**Plant Location**	**Commissioning Date**
JEP	74	Old Harbour	1995
JPPC	61	Rockfort	1996
Wigton Wind Farm	20.7	Manchester	2004

[7]

A review of the data above reveals the fact that the steam units, which supply the base load demand, are all of an average age of over thirty five years. Given the current load demand, which is discussed below, the steam units will not at anytime be able to supply the base load demand with the requisite reserve margin of 25 to 30%. This reality means that the need to replace some units within the system will become a necessity. As indicated above, replacement and ultimately commissioning of new generating facilities will be undertaken by the LCEP; which ideally seeks to replace and increase generation using the cheapest technology [16].

In addition to needing replacement, the steam units are supported by output from the Independent Power (IPP) Suppliers in order to satisfy the base load. This is further illustrated by the demand supply curve, for the year 2003, shown in figure 2.10. The fact that all IPPs use diesel as fuel, results in high cost of electricity to consumers; given that the JPSCo is able to recover costs regardless of the fuel type used for generation. Conventional wisdom dictates that steam and hydro based units would have the lowest operating costs, however the low operating efficiency of some of the steam units rank their costs much higher than that of some diesel units.

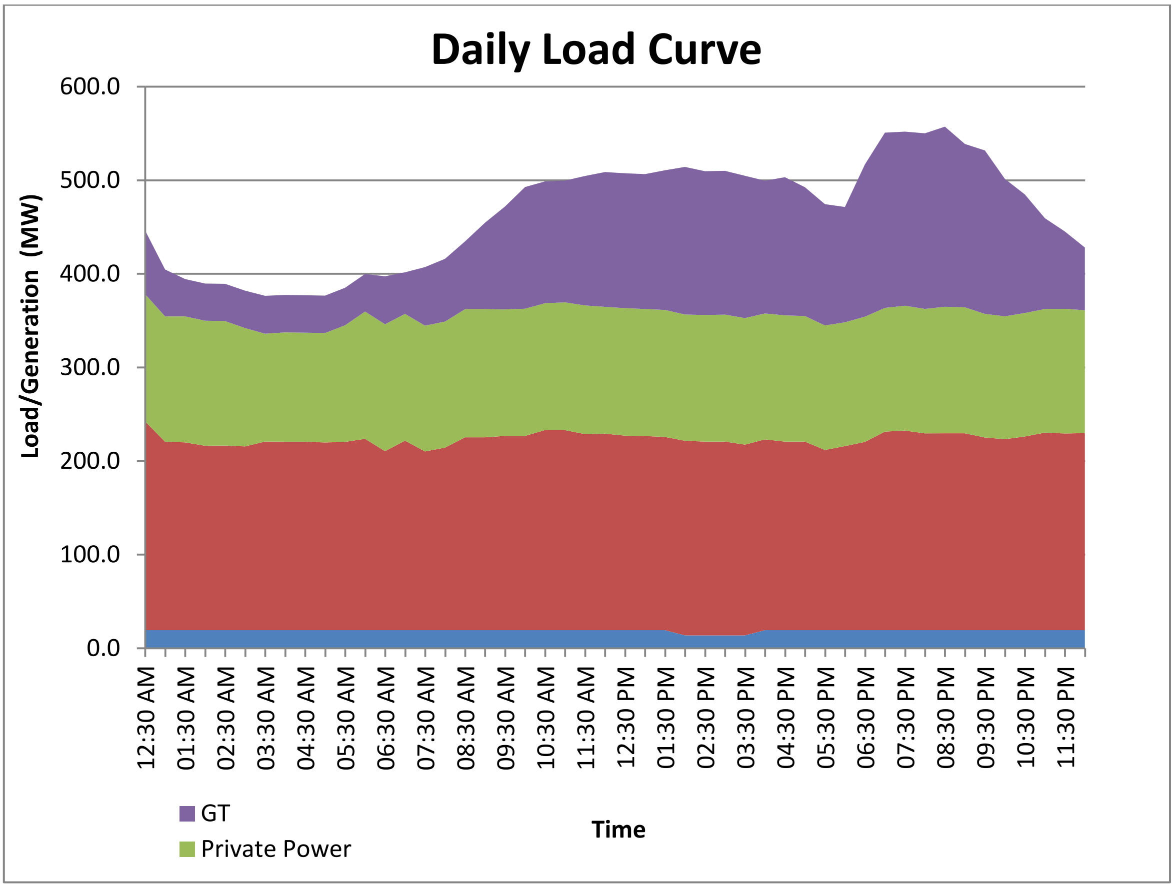

Figure 2.10: Load Profile and Corresponding Generation Supply

[20]

The Hydroelectric plants have an average age of over forty years; as a consequence unavailability for long periods is common place. However as indicated by the figure above, these are run continuously, when available.

2.5.4 Load Profile

Based on the 2006 annual report of the JPSCo, revenues from the various sector groups as a percentage of total output was as shown in figure 2.11.

As a single block, residential consumption represents, by far, the largest subsector of consumers.

The capital city Kingston represents the bulk of industrial and commercial activity on the island thereby justifying the 223 MW installed generating capacity. This however does not fully satisfy the demand in this area, hence requiring support from the other facilities. The other generation area in Montego-Bay is the main tourist area and hence the demand is primarily from the hotel sector.

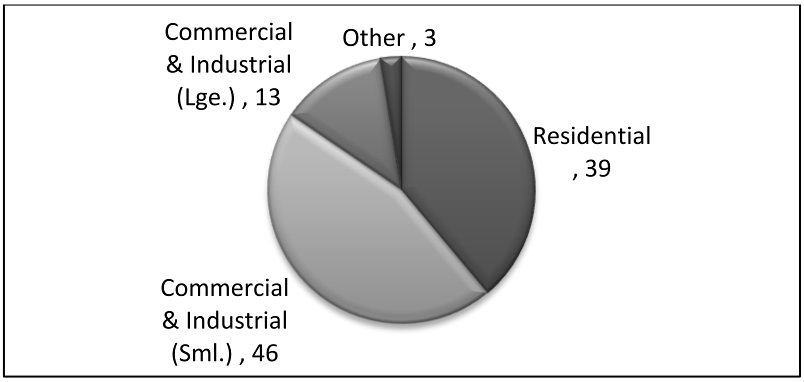

Figure 2.11: JPSCo Load Demand Profile

[21]

The other source of major demand comes from tourism activities along the northern shores and the western tip of the Island, representing commercial type load. Other activities that require significant electricity input are sugar and alumina production; however these entities are all self-sufficient in this regard and remain connected to the grid for redundancy support.

2.5.5 Daily Load Dynamics

Unlike industrial nations, the island's peak demand results from domestic usage as can be seen from its typical load profile shown Figure 2.12.

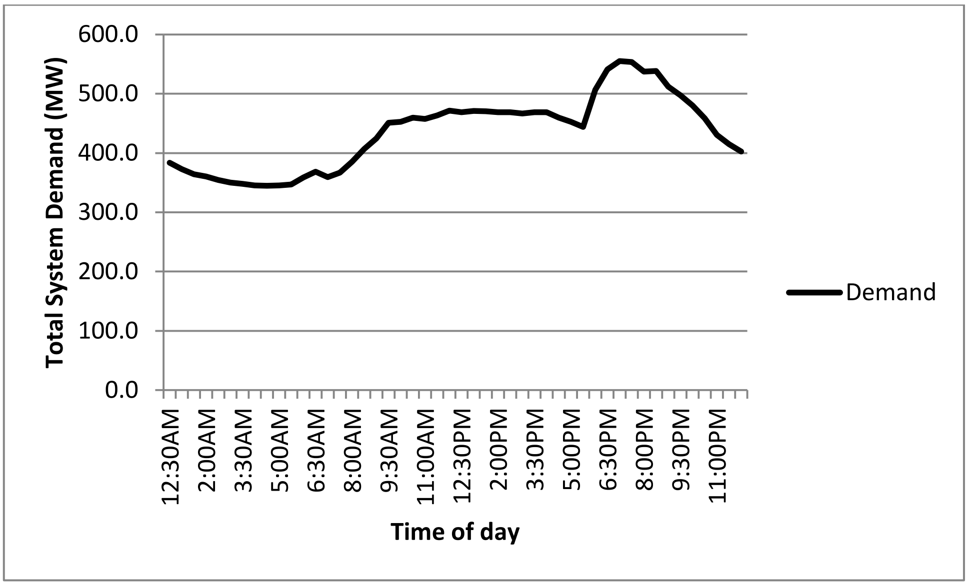

Figure 2.12: Load Demand for a Typical Workday in 2003

Figure 2.13 highlights the fact that there is very little variation in the load pattern on weekdays. While weekend demand is lower during midday hours, it can be seen that the peak demand irrespective of the day being considered, remains high during the evenings providing further justification of domestic demand being the major contributor.

The peak demands in the years 2006, 2007 and 2008 were 626, 629, and 622 MW respectively. This is an indication that there has been a levelling off of the demand over the period.

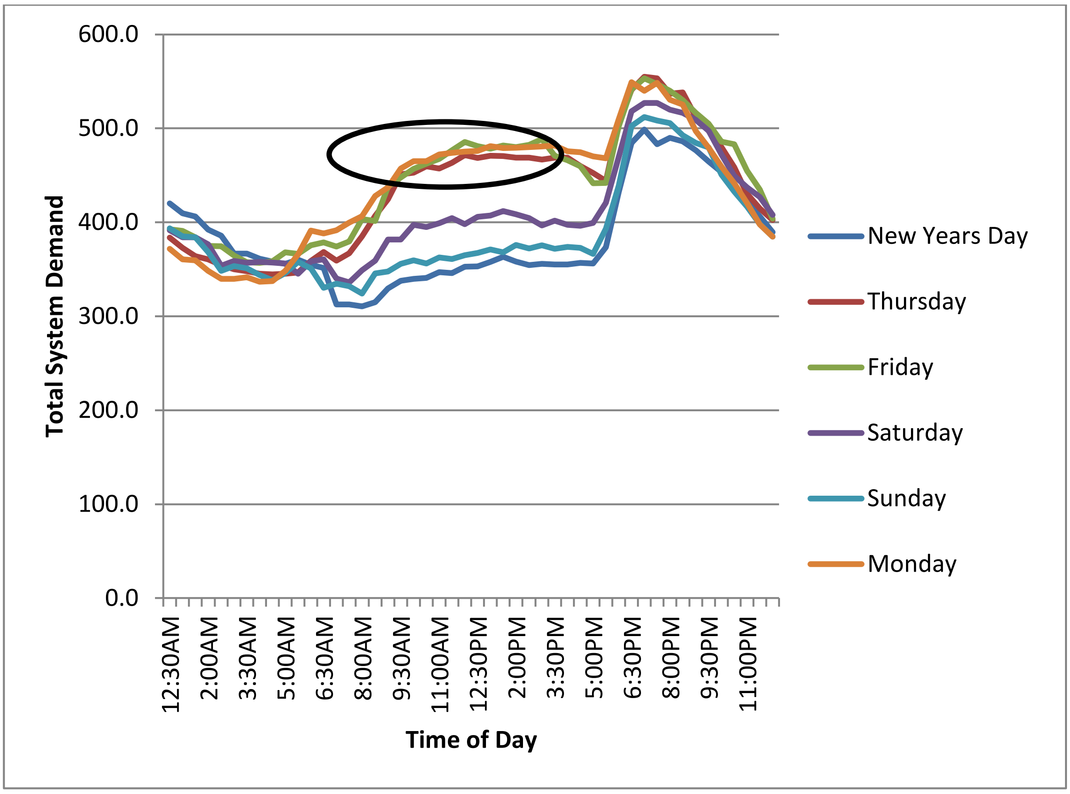

Figure 2.13: Load Demand for a Typical Workday, Weekend and Holiday

The load curve profile, over this period, has also not changed significantly.

Conclusion

The use of oil and other energy sources in the generation of electrical energy and their use across the Island have been established. Additionally the attempts made in identifying alternatives as well as the plans for the establishment of future energy sources have been discussed. The framework with respect to the market has also been highlighted.

Finally the physical structure to support the transmission of the electricity produced was also reviewed. It is now instructive to focus on some of the challenges that may accrue as well as the suitability of one of the renewable sources available for use, in the foregoing chapter.

CHAPTER 3

Issues Associated with Renewable Energy Use

Chapter three explores the issues associated with renewable energy use. It looks first at wind energy in power systems by considering aspects important to integration in networks. The chapter also highlights the renewable energy used in four select countries of the Caribbean region, in relation to the governmental policy positions that support them. A comparison is made with select countries of the European Union and the policy considerations that informed and impacted the expansion of the use of renewable technologies.
The chapter concludes by briefly reviewing some of the work done in renewable energy in Jamaica.

3.1 Wind Energy in Power Systems

Proper operation of a power system requires that several operational targets are met. Among those considered important are:

1. The ability to effectively and efficiently match demand with supply
2. Maintenance of nominal voltage levels and quality
3. The ability to withstand or quickly recover from disturbances

These criteria broadly describe the adequacy and security of the system. The adequacy of the system describes the amount of production and transmission capacity in varying load situations while security defines its response to disturbance.

Given the inherent nature of wind, as a resource, these criteria provide immense challenges for the operation of the network. It is therefore necessary to identify how the output from this technology is treated, in meeting these goals.

The use of wind for the production of electrical energy in not a new phenomenon, however, since the 1980s the technology has developed to the stage of being considered as one that is mature. The increase in the use of wind energy has therefore resulted in due consideration given to its impact on existing power networks. While some economies have embraced the technology as a “cleaner” alternative, others have seen it foisted upon them out of the need for an alternative source. Regardless of the reasons for its use, it is critically important for the engineering impact of the technology to be investigated.

The use of wind energy can only be made, based on the level of availability of the resource in a particular area, country or region. It is therefore necessary to conduct local analysis of its impact on that system. Experiences of wind power integration in other networks/systems cannot therefore be translated into another; however the information garnered, from such experience can be used as a template for the analysis.

3.1.1 Capacity Considerations

3.1.1.1 Wind – Intermittent or Variable

Intermittent refers to the act of stopping and starting at intervals. Such intervals can be period or aperiodic. On the other hand, variability speaks to the characteristic of having no fixed quantitative value. From these definitions it is obvious that the description of electricity from wind as an intermittent quantity is inaccurate. Wind electricity is therefore better classified as a variable commodity. It is therefore the variability and its impact on the network that must be firstly analysed.

As a variable commodity any attempt to analyze its effectiveness on a power system by assessing peaks and troughs of the system load will inevitably result in error. It would therefore be more accurate to base this assessment on the variation of both the input wind and the system load. To achieve this goal there needs to be acceptable means of forecasting the load demand as well as the wind resource. While experience has resulted in robust methods/tools for forecasting demand, forecasting wind power for effective generation dispatch is still an evolving science.

The overall impact must also be determined with due consideration for the other generators in the system. Removing and analyzing a single turbine or farm will lead to unreliable results. In the event of a network being supplied by multiple farms, in wide geographically diverse areas, the benefit of wind is better realized when assessed as a whole. Such an approach is based on the fact that the wind resource will not be present or absent in all areas simultaneously. Unlike fossil fuel plants, wind turbines result in a gradual loss as against a sudden loss of supply, whether from breakdown or a tapering off of the wind, but results in a gradual decrease in output. This gradual decrease facilitates network operators to supply the demand by other sources.

3.1.1.2 Meeting Demand with Wind

Based on studies conducted in Europe it has been found that current technology is able to facilitate 20-25% penetration from wind energy. This advancement has been heavily based on the development in generator design and control. The double fed induction generator (DFIG) has been the main driving force behind this advancement. Figures released by the European Wind Energy Association (EWEA) in 2005 shows that this generator accounts for approximately forty five percent (45%) of the total installed capacity in the EU. Not only have the DFIG facilitated better grid control mechanisms but also the manufacture of larger units.

While this technology has facilitated better operating parameters such as voltage control, it has also resulted in a reduction in the reliability of turbines. Most generators of output capacity less than 1MW are fixed speed units, which are very robust and relatively cheap. On the other hand, larger units (DFIG and Synchronous Generators) are variable speed with an electrical converter, making them more prone to failure. Consideration must therefore be given to the reliability of not only individual units but that of the farm. This however will not be a focus of this study.

Load factor (capacity factor) refers to the ratio of the average generated to the rated power of a system. The load factor of a typical wind generator is estimated to be between twenty five and thirty percent (25 – 30%). Other estimates, in high wind areas, are set at a high of forty percent (40%) **[22]**. Fossil fuel units on the other hand have load factors upward of ninety percent (90%). The significant difference between these values gives rise to need to carefully determine the cost, to the system, of operating these units. While the fuel input for wind turbines is zero, one needs to consider the installed capacity required to meet a particular demand in comparison to that of other plants. The load factor, based on forecasts, also gives an indication of the potential output to meet daily demand**.**

The power curve below shows that the rate of variability of the output power increases while operating between 25 and 75% of rated output. This fact should therefore be considered when conducting studies on areas where there is high wind input.

Another key measure is that of capacity credit. In general, capacity credit is a measure of the capability of a new plant to increase the reliability of the power system. In other words it determines the power that can be relied on from that unit. The estimation of capacity credit is based on assessing the potential capabilities of the system with and without the wind power input.

In looking therefore at how power from wind energy helps to meet the system demand, one must consider the output with respect to time.

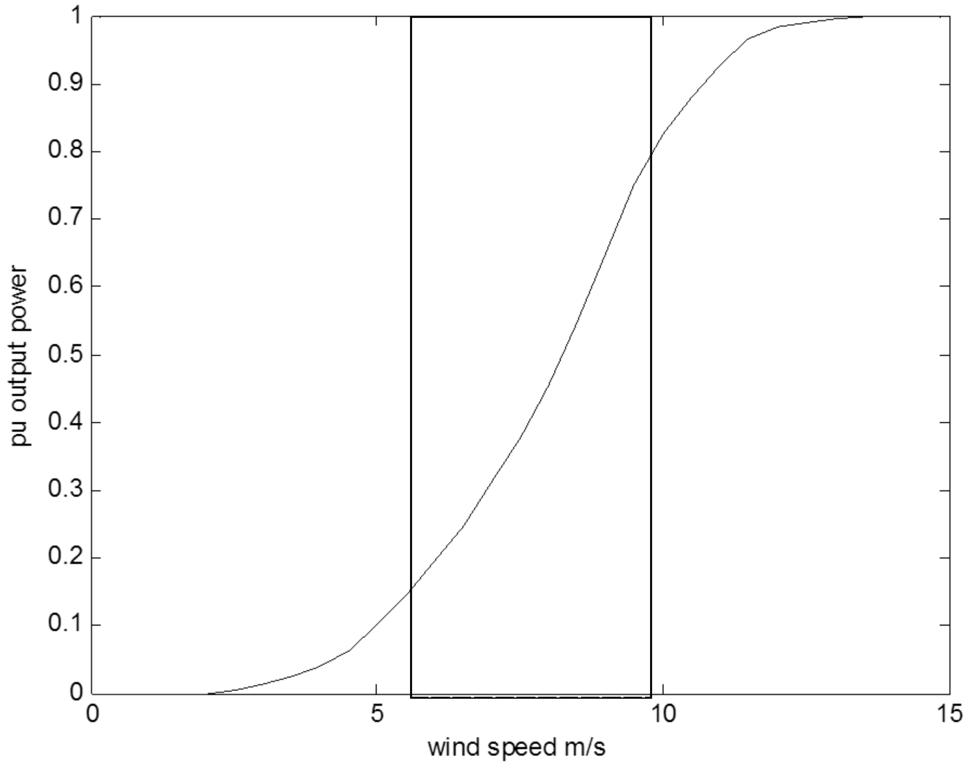

Figure 3.1: Per unit power curve of wind turbine with DFIG

It is then possible to determine its impact on

1. Transients variations – second by second analysis (which will not be an area of focus for this study)

2. Daily variations – half hourly to hourly analysis, to determine adequacy

3. Seasonal variations, which informs strategic planning.

The impact assessment based on these time scales gives a much more holistic solution to the ability of wind to meet system demand. However, given the uncertainty with determining and by extension managing the output, management of the demand can be the only solution. Although rarely carried out in developed markets, demand side management is frequently used in the Jamaican network. It would therefore be instructive to establish how an increased capacity credit resulting from wind would impact this operational option for the network.

3.1.1.3 Forecasting

It is a given that forecasting the wind resource affects both unit commitment and power system planning. It is also understood that forecasting must be carried out with due consideration given to the area for which system analysis takes place. This is based on the fact that the forecast is dependent, among other things, on the terrain on which the potential farm will be sited and the prevailing temperature gradient. The importance of this undertaking is however dependent on the operating environment in which wind energy is consumed. Although several tools exists for forecasting the extent to which further investment in this area will take place is dependent on its importance to the various participants in the wind energy market.

Within the UK generators (licensed generators i.e. supplying more than 100MW or those that are smaller but opting for full license), under the British Electricity Trading and Transmission Arrangements (BETTA), are required to provide information to the National Grid Electricity Transmission (NGET) of its contracted output on a half hourly basis, at least one hour ahead of real time. [14]. Subject to acceptance by NGET, the generator is thereafter required to supply the power as per the agreement. Should the generator fail to supply according to contract by either over or undersupplying, a penalty will be applied. Under such a scheme it is in the interest of a licensed wind generator to invest heavily in forecasting technology. The alternative to such an arrangement is established where embedded generators, including wind, can sell their supply via a pool arrangement. The balancing effect of those under and over supplying would be realised. However under such a scheme the issue of forecasting would be shared by the individual generator and the manager of the pool.

An almost contradictory scheme operates in Germany where, by edict, the system operator is obliged to accept the electricity generated from wind. The operator therefore has a greater interest in the ability to forecast the availability of the wind resource.

In California the Participating in Intermittent Resource Programme (PIRP) was introduced. It operates by having generators subscribing to the system operator who carries out forecasts on their behalf. The balancing arrangement to meet demand is similar to that in the UK. Here however the system operator has the greatest interest in forecasting tool.

3.1.1.4 Frequency Control

Maintenance of system frequency is part of the contractual agreement between the consumer and the supplier. Deviation in system frequency will be dependent on the extent to which the load-generation balance can be achieved and maintained. While this balance is heavily dependent of the generator to supply the agreed output, consideration must be given to the unexpected loss of significant generation and load when considering the impact on frequency. It will be therefore necessary to conduct contingency analyses with and without the wind energy.

3.1.1.5 Voltage Control

The voltage level within a transmission system is kept at acceptable level by adjusting the reactive power flow. Generators and special equipment, such as FACTS devices, control this reactive power. In order to manage the voltage level during disturbances, reactive reserves in power plants are allocated to the system. These reserves are used mainly as primary reserves in order to guarantee that the voltage level of the power system remains stable during the disturbance.

Fixed speed wind turbines inevitably draw reactive power from the grid. The capacitor bank associated with these machines provide for reactive power compensation. The magnitude of the reactive power required from the grid is reduced by using soft starters. DFIGs and Synchronous machines are able to absorb or supply reactive power to the grid. However, some operators require wind generators to supply power to the grid at unity power factor.

3.2 Renewable Energy use in the Caribbean

Increasing costs associated with fossil fuel generation coupled with the recognition and acceptance of the finiteness of this resource has, in part, contributed to the growing popularity of alternative energy generation. International environmental treaties have also forced many states, primarily developed states, to consciously review their use of fuels.

Countries within the Caribbean region, with the exception of Trinidad and Tobago, are all dependent on imports of fossil fuels for electricity generation. However many of these countries are rich in natural resources that can provide a significant portion of their domestic needs in a sustainable way. Geothermal, Solar, Hydro and Wind are but four of the technologies that these countries possess. While targets have been set for the increased use/exploitation of these resources, the relevant mechanisms to facilitate such expansions are in need of revision and or creation

The culture, economics and governmental structure of the majority of islands that make up the Caribbean community (CARICOM), are direct derivatives of their colonial past. Independence for the majority of these nations began in the 1960s. As would have been expected a cost effective, sustainable energy supply is a key component for the development of the economies of these countries. While many CARICOM countries were able to establish their own electricity generation facilities through governmental input, it soon emerged that further expansion would require the involvement of non-governmental institutions. This reality came at a price, as special incentives, such as exclusive operation licenses, were offered to facilitate the investment. [23]

The 1960s expansion was predicated on the seemingly inexhaustible oil, which was seen then as the only available option. It was not until the shock of the 1970s oil market crisis that governments, including those from the Caribbean region, began to recognise the need to look towards alternative energy. While this initially focused on heating systems, electricity generation gained greater prominence following the establishment of the Kyoto protocol.

While CARICOM continued to expand on the use of oil and gas, the European Union through Directive 2001/77/EC (RES-E), established a group target for the use of energy from Renewable Energy Sources (RES). Members as well as potential members of this grouping, were given National targets as a subset of the EU's overall RES-E objective. While longstanding member countries have had the benefit of establishing and reviewing their own targets, it is instructive to consider those nations that have been forced to review their operations to meet the Union's objective in pursuance of accession.

Many Eastern European countries, as defined by the United Nations, have evolved from an era of centralised control of many aspects of their economy including electricity production. For many years the bulk of the electricity was produced from coal and, for many, antiquated nuclear plants. [24]. As the world continues to evolve economically and technologically, these countries (as groups and individually) are forced to adopt new ways of life in guaranteeing sustainable development. Some of the necessary development strategies are contingent on governmental and/or regional policies. Diversification in energy supply is one such development that is affected.

The need therefore to make the shift in the level of RES-E makes the comparison of these nations worthy of consideration, as a guide to the barriers of similar levels of expansion in CARICOM.

3.2.1 Operation Framework

3.2.1.1 CARICOM

Figure 3.2 highlights the diversity in the fuel types used in electricity production in four select countries of the Caribbean region. As the only oil producing nation, among those highlighted, Trinidad and Tobago uses natural gas to produce all (100%) of its electricity. This is in total contrast to its neighbour ST. Lucia which utilizes automotive diesel oil for its total electricity needs.

The energy mix of Guyana shows generation from heavy fuel oil and automotive diesel. While this dependence on fossil fuels is representative of not only the selected countries but across the region, the Guyana Energy agency reports that the available electrical energy potential, from hydro generation, is approximately seven gigawatts (7 GW). Notwithstanding this potential, of the peak demand, in 2000, of approximately 94.5 MW only 0.5% was supplied from Hydro. [25] [26] [27] [19]

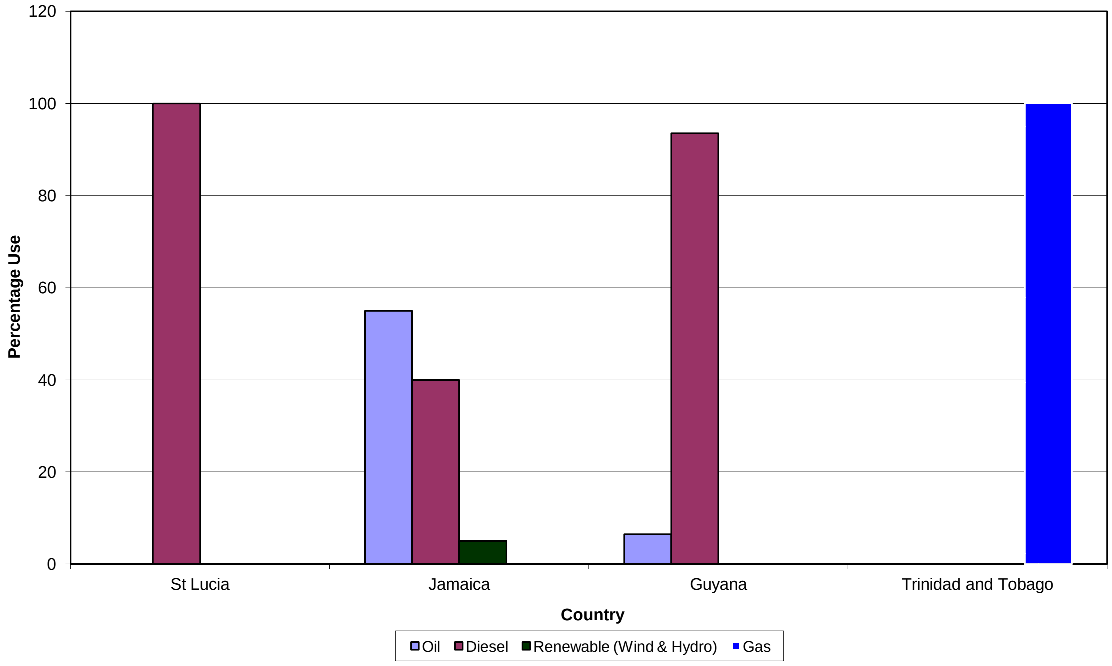

Figure 3.2: Electricity production by fuel type, used in CARICOM

The approximately 5% of electricity produced from RES in Jamaica is equally divided between hydro and wind[7].

Though a relatively small sample, the experience regarding the dependence of fossil fuels is replicated throughout the region. This fossil fuel dependency indicates the susceptibility of these economies to variations in world oil prices.

3.2.1.2 EU Countries

Figure 3.3 shows, as a percentage of total production of electricity, the fuels used by four former eastern block countries during the year 2000. By far, coal is the most heavily used fuel among these nations. The higher percentage use in the Czech Republic and Poland is a reflection of coal's local availability.

Nuclear production represents a significant component of the total electrical energy consumed for the Czech Republic, Bulgaria and Hungary. By way of ranking, gas produced electricity is the next most significant contributor.

[7] Based on installed capacity

The use of oil in Hungary's production is a direct consequence of its local availability. On the other hand, although imported, the country also produces a significant amount of its electricity from Russian gas supplies.

Hydro electricity, as a RES source reflects the greatest use, albeit small, among the countries considered. [28]

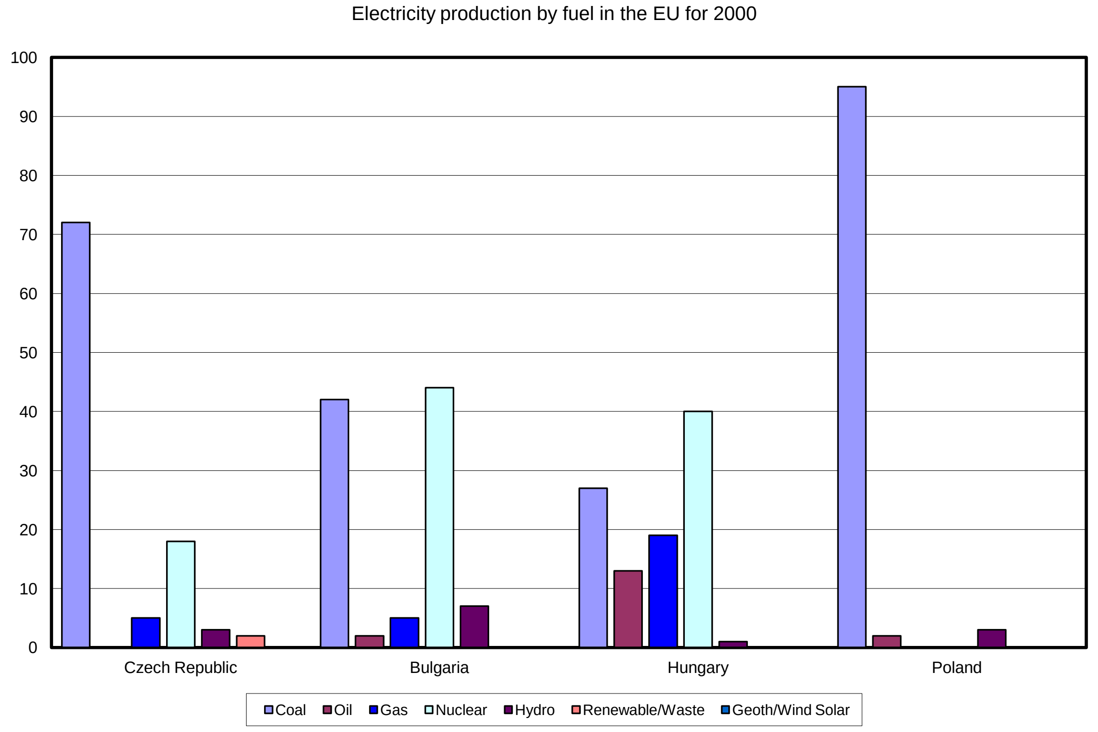

Figure 3.3: Electricity production by fuel type in the EU for 2000

Percentage production in the year 2004 for the same territories is shown in Figure 3.4 The date is significant given that this coincides with the accession to full membership of the European Union by Poland, Hungary and the Czech Republic. This move by the countries required them to operate in conformity with many European Union regulations. Among these were safety and pollution, which are impacted by electricity production. (2001/77/EC (RES-E))

With respect to the Czech Republic there was significant decline in the use of coal and a corresponding sharp increase in the use of Nuclear. While as percentage renewables accounted for less of the total production, their production levels remained constant.

The use of gas, especially in Hungary, resulted in a commensurate decline in oil. The gas expansion was also realized in Poland as well as Bulgaria.

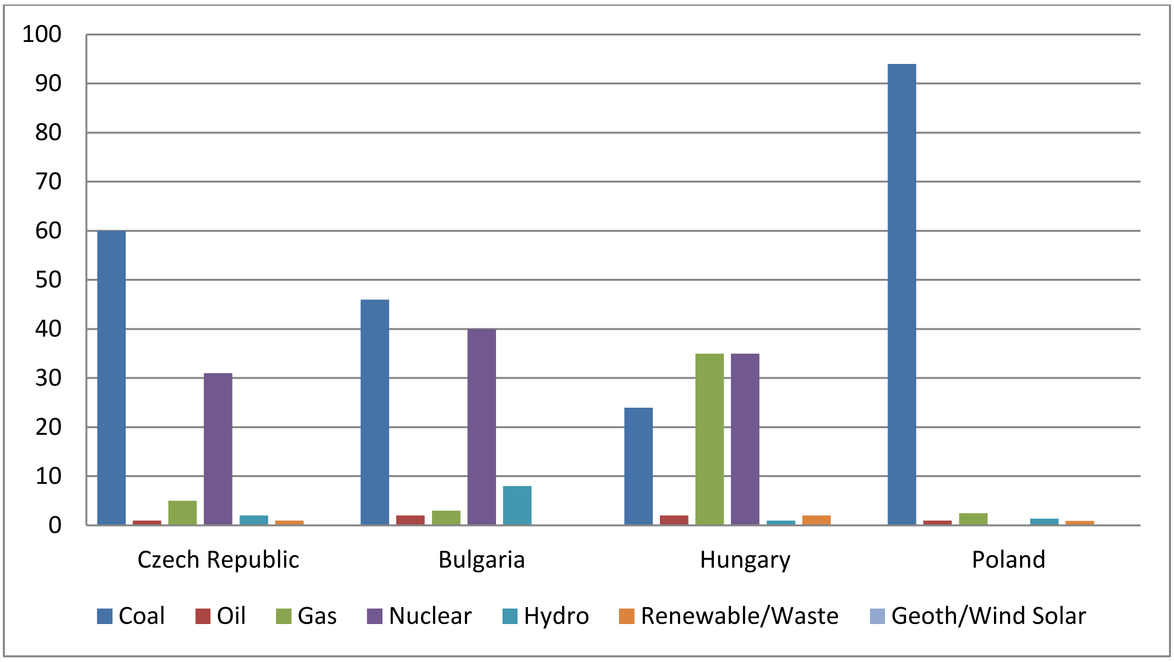

Figure 3.4: Electricity production by fuel type in the EU for 2004

Poland and Hungary also saw an expansion in the use of renewable waste as part of their electricity production.

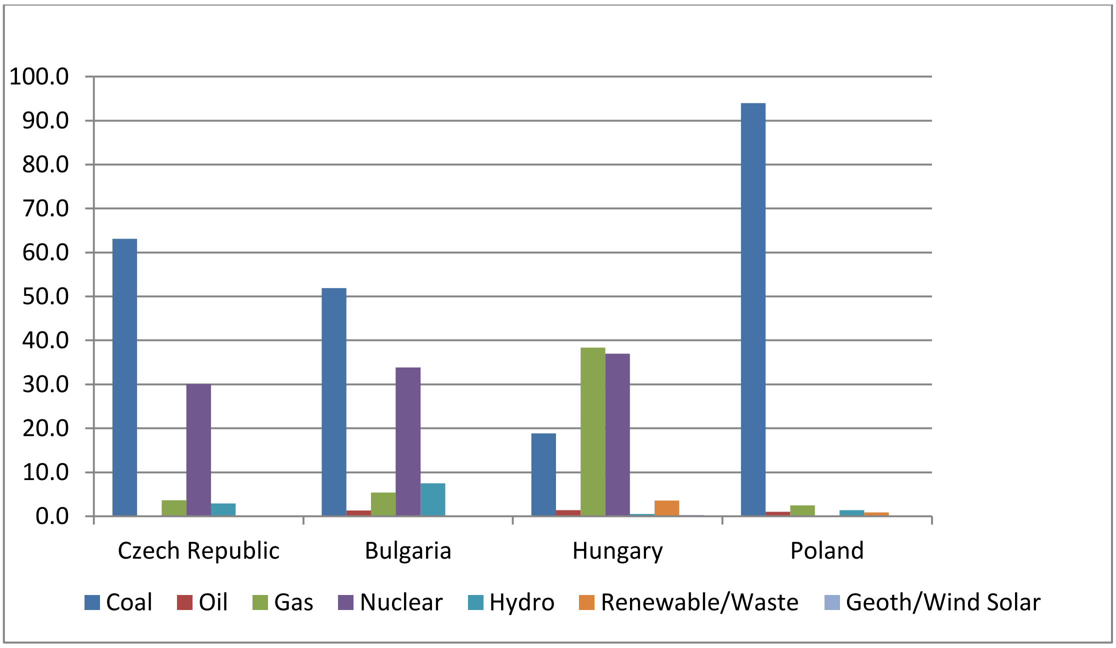

Figure 3.5: Electricity production by fuel in the EU for 2007

Increases in the use of RES continued into 2007. Although small[8], wind energy production saw a significant increase in this year. Contribution from this source to the overall production levels ranged from a low of 47 GWh to 512 GWh.
With the exception of Bulgaria all the countries considered reduced their use of coal in electricity production. Nevertheless the key achievement with respect to RES use is the fact that over the seven years all four territories experience an expansion.

3.2.2 Market Structure

3.2.2.1 EU Countries

As former members of the “Eastern Block”, Poland Hungary, Bulgaria and the Czech Republic operated state controlled, subsidized electricity markets. However as a prerequisite to entry into the European Union these countries were forced to liberalize their energy sectors. The models adopted for each nation varied in addition to the extent of the liberalization achieved. [29]
At its accession to membership of the EU in 2004, Poland was in the fifth year of its gradual roll out towards a market structure. Between 1999 and 2005 consumers of varying levels of consumption[9] were given access to the grid. To further strengthen market activity an energy regulation authority was formed[10]. The authority was required to, among other things, issue generation licenses, approve and manage tariffs and control electricity quality standards [30]. Notwithstanding the fact that many of the generation facilities have been commercialised, the ownership initially remained government or government agency owned. Distribution however, is carried out by some thirty three (33) companies, which like generation were mostly owned initially by governmental institutions. The transmission system however is fully owned by the state owned Polish Power Grid Company.
The Czech Republic has liberalised its electricity market to the extent that beginning with large companies, consumers can now choose their electricity supplier. This move is also supported by the privatisation of supply and distribution operations. Although deemed as having the most liberalised market among the group, the Czech Republic electricity market is dominated by three major companies. The CEZ which is largest is involved in distribution, supply as well as a generation. The company produces approximately 73% of all the electricity in the country.

[8] Not clearly reflected on graphs
[9] The total annual consumption for successive years between 1999 and 2005 were not less than 500 GWh, 100 GWh, 40 GWh, 10 GWh, 1 GWh, all consumers
[10] Urz d Regulacji Energetyki - URE

In the case of Hungary, large consumers can choose their suppliers with the caveat that not more than 50% of the supplied energy is imported. In addition, household consumers still remain under government subsidized programmes. Bulgaria has taken the necessary steps to privatise the majority of its generation facilities. Among these measures is the establishment of a system operator which manages an electricity balance market. [9] [31]

The Hungarian and Bulgarian markets although "liberalised", still have a number of challenges. State control in Hungary is still evident. Additionally, the network operator is also involved in generation. In Bulgaria, subsidies are still being applied to low voltage customers, through the redistribution of profits from the network operator. [32]

3.2.2.2 CARICOM

The St. Lucian and Jamaican markets are controlled by fully integrated companies that own generation, transmission and distribution facilities. These companies operate on the basis of total cost recovery and guaranteed minimum profits. In the case of Jamaica, cost recovery is also based on the company's monthly fuel costs and those associated with the independent power producers (IPP) from which it purchases power. At present all IPPs, with the exception of the government owned wind farm, use automotive diesel for electricity production. [33]

In Trinidad and Tobago the government owned Trinidad and Tobago Electricity Commission (T&TEC) is responsible for the design, construction, operation and maintenance of the country's electrical transmission and distribution network. As the sole retailer of electric power, the utility supplies the commodity to customers on both islands via a single interconnected grid. It purchases the bulk electric power from independent generation companies for resale, and is also responsible for securing the fuel supplies for these companies. [27]

The Guyana electricity market is controlled by the government owned Guyana Power and Light Inc. (GPL) Company. The GPL was originally formed as a government/ private partnership with a British based consortium and the Commonwealth Development Corporation (CDC). Under this new entity a "semi-liberalised" market structure was developed, where power was purchased from private power producers. Although the company has now reverted to total state control, the influence of the British in establishing greater private investment in generation has continued and now forms the core of the country's electricity policy. [26]

3.2.3 Renewable Energy Policies

3.2.3.1 The Czech Republic

Following on from removing the monopoly based electricity market, as required by the EU, the Czech Republic has, as of 2004, implemented a renewable energy policy. Among other things, the policy provides for payment to renewable energy generators above market price, up to 2006. Thereafter this provision has benefited only small generators (below 200kW). Distributors are also obliged to connect generators with output at this level.

Larger suppliers however, are able to benefit from being able to sell green certificates to non-renewable source generators. The value of these certificates is based on the type of renewable source used. This approach is supported by the fact that non-renewable energy producers face extremely high penalties for any shortfall in their annual quotas [29].

3.2.3.2 Poland

The policy adopted in Poland is in large measure similar to that used in the Czech Republic. Unlike the licensing requirements for conventional source generators, there is not a similar need RESE generators with a capacity less than 50 MW, prior to 2007. There is an obligation for enterprises which sell electricity to end-users to purchase electricity produced from renewable sources.

To further strengthen the use of RES-E, supply companies are required to obtain specified number of green certificates[11]. The certificate, among other things, identifies the renewable source from which the energy is produced. Should the producer fail to meet its quota punitive sanctions are applied [34].

3.2.3.3 Hungary

At the initial introduction of a renewable energy policy, there was mandatory purchase of available energy from renewable sources. This was further boosted by preferential feed-in tariffs to suppliers. The policy was applicable to all renewable energy sources.

[11] The quota is increased annually from 7% in 2008 to 10.4% between 2010/14

Since an amendment in 2005, feed-in tariffs became technology specific, which are further guaranteed for the lifetime of the installation. The amendment also facilitates the introduction of trading in green certificates, which when implemented will replace the use of feed-in tariffs.

An indirect policy support for renewable energy is the implementation of an environmental burden tariff. This tariff is paid by any entity which produces Nox gases, CO_2 or solid waste. The implication being that the cost of producing conventional energy will gradually increase; thereby making RES based technology more competitive [34] [29]

3.2.3.4 Bulgaria

The key plank of the Bulgarian policy for renewable energy sources is the mandatory purchase of electricity, for generators up to 10 MW, at preferential prices.
Subsequent to this policy, based on grid connection difficulties, feed-in tariffs have become specific to technology and capacity of installations. Trading however in green certificates replaces this arrangement as of 2007 [35] [34].

3.2.3.5 Jamaica

The policy governing the renewable energy sector for Jamaica is, for the most part, the responsibility of the Utilities regulator [36] [13]. The policy[12] sets out, inter alia:

1. That the Minster responsible should review the renewable energy targets, giving consideration to security of the public electricity network and the rates established by the regulator

2. The system operator is obliged to receive power from "qualified" generators at the rates set by the regulator.
    a. The regulator should

        i. establish market rules to encourage the introduction and expansion of these generators

[12] 2006 energy policy revised in the 2009-2030 document

ii. develop and publish rules for interconnection

3. Any additional cost to the system resulting from the connection of renewable source must be passed on to the consumer.

4. To offset the capital costs associated with this generation, a national energy fund will be developed, which will provide seed funding for qualified ventures.

5. In addition to duty exemptions and accelerated depreciation schemes, the government will also seek funding from regional and extra regional bodies that support the use of renewables.

3.2.3.6 St. Lucia

Given the current eighty (80) year license, now in its forty second (42^{nd}) year, enjoyed by the sole electricity generator, the introduction of renewable energy to the system will be based on bilateral agreement between the government and the utility company. The current licensing agreement with the provider, The St. Lucia Electricity Services (LUCELEC), prohibits the private establishment or distribution or co-generation of electricity. The country's renewable energy policy is therefore solely geared towards heating/cooling schemes [25].

3.2.3.7 Trinidad

The Trinidadian “renewable energy policy” can be summed up from statements from the Ministry of Energy and Energy Resources. In essence the ministry recognizes the overall obligation to support efforts in developing sustainable energy systems. However there is a clear indication that given the current dependence on natural gas, the government has no immediate plans to pursue efforts in finding renewable alternatives [27].

3.2.3.8 Guyana

The Guyanese renewable energy policy is geared towards enhancement of domestic production as well as tapping the vast hydro potential for export.

The policy provides for

1. The establishment of Power Purchase Agreements, with the mandatory purchase of electricity from RES suppliers at avoided cost.
2. The exemption from taxation of all materials and equipment used for renewable energy production.

The overall policy is backed up by governmental incentives for industrial development for foreign investors [26].

3.2.4 RES Use and Analysis in the E.U. and CARICOM

3.2.4.1 European Union

Figures 3.6 to 3.9 shows the relative percentage use, as a total of the renewable energy, used for electricity production, in Poland, Hungary, Bulgaria and the Czech Republic, in 2000, 2004 and 2007.

The fluctuating levels of the different sources make it difficult to make simple definitive statements about growth. This fluctuation was also based on the fact that the figures are based on production levels and not installed capacities. Being for the most part, variable supplies which are dependent on factors such as weather, the declining output is not an indication of increased investment in the technology.

A key observation however is that for three of the four countries, there was an increase in the range of technologies in use over the period.

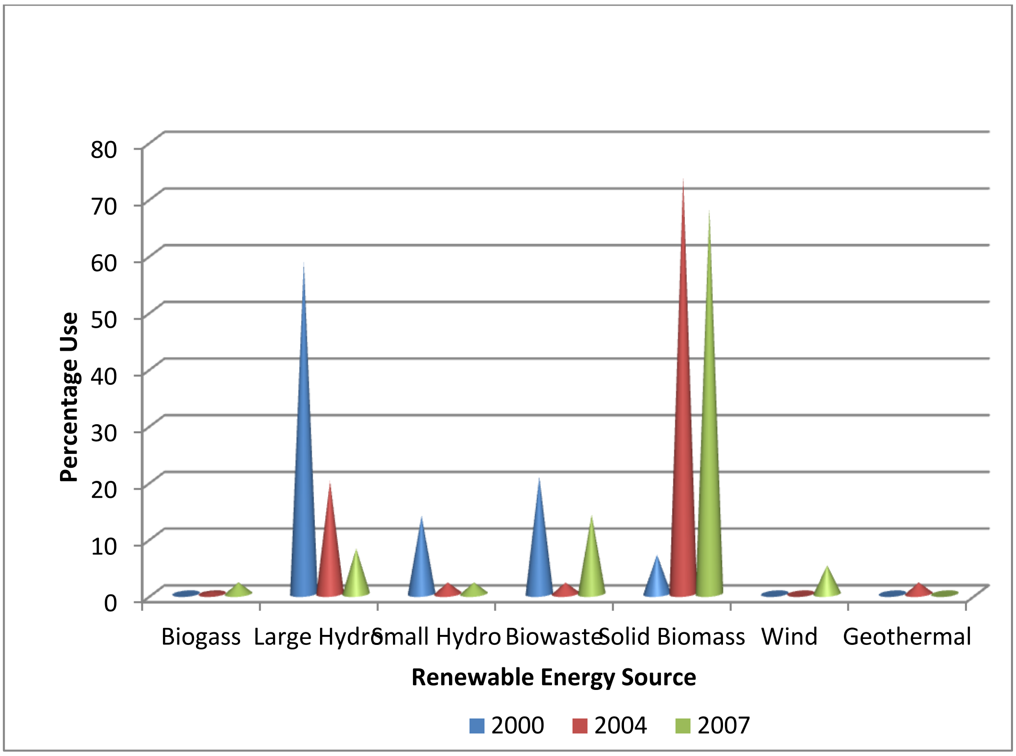

Figure 3.6: Electrical Energy from RES – Hungary

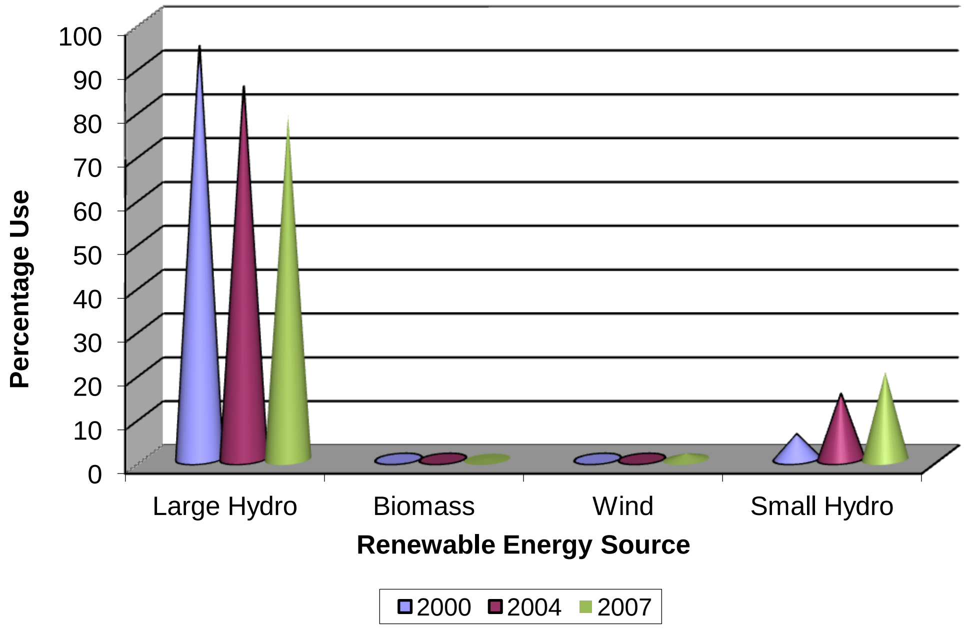

Figure 3.7: Electrical Energy from RES – Bulgaria

The near 250% increase in the use of renewables in electricity production in Hungary between 2000 and 2004 was based primarily on a significant increase in the use of biomass [29]. The increase resulted from the establishment of co-firing plants which replaced coal with gas and biomass. Overall, hydro-electric production remained constant over the period under review.

The significant increase in wind after 2004 was based, in part, on the new feed-in tariff structure which became technology specific in 2005. Given the capacity restrictions in the other sources, it is envisaged that wind will be the main renewable source being exploited in the country. Although not being able to attain its established percentage goal, the country has made steady progress towards its achievement; which has been supported by the policy directives of government and prevailing market structure.

The change experienced in Bulgaria is by far the best evidence of the impact of policy. There was a major shift from large hydro to small hydro plants given that the policy supported preferential feed-in tariffs to generators up to 10 MW. Greater diversity in RES use in Bulgaria is hampered by the availability of the resource. The market though not fully liberalised has not prevented the country from being on target to achieve its established goal. Similar to Hungary there was marginal increase in the use of wind energy

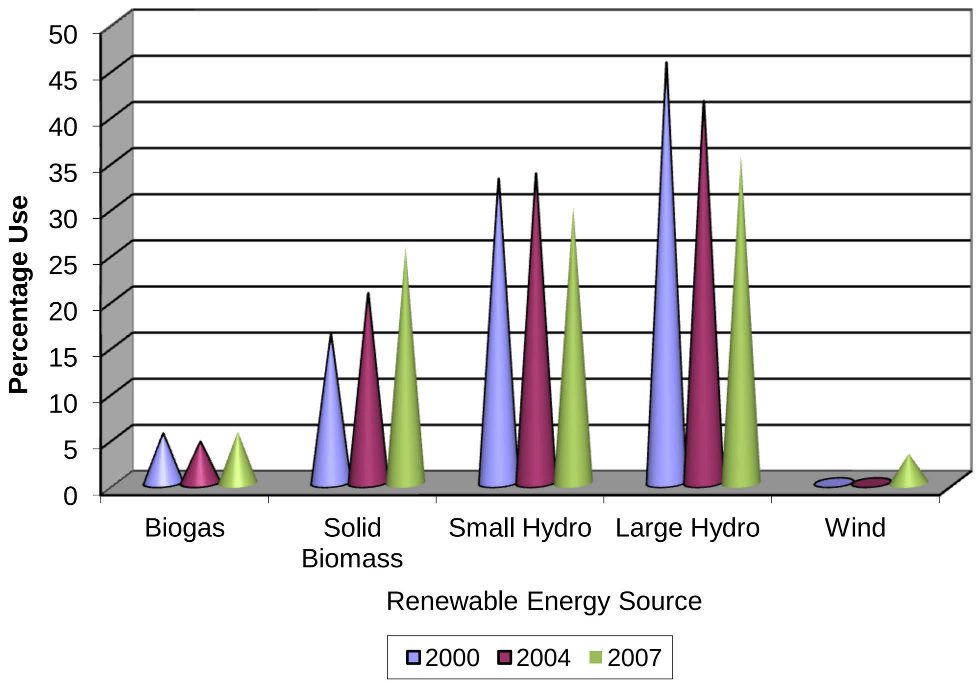

Figure 3.8: Electrical Energy from RES – Czech Republic

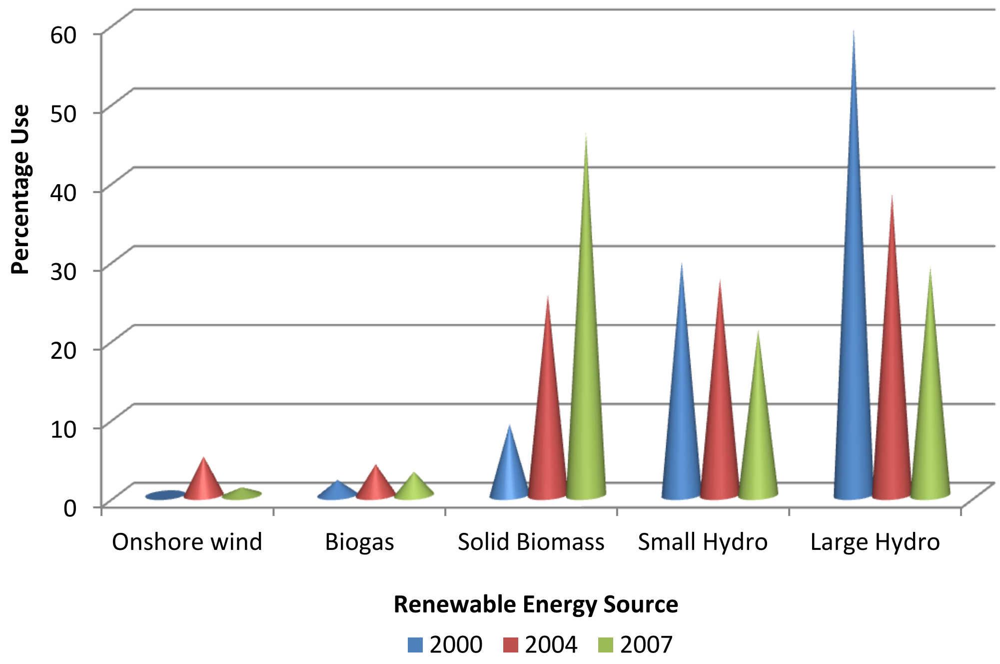

Figure 3.9: Electrical Energy from RES - Poland

Hydro- electricity has historically been a major contributor to the total electricity supply in the Czech Republic. However the most significant change occurred in the use of biomass, which had a 6 percentage point increase between 2000 and 2004. The production levels for this source, continued to increase into 2007.

Although coal and lignite remains the main contributor to the electricity production in Poland, the greatest significant feature is the level of diversity in the use of RES-E. Although at significantly different levels of increase, growth biomass and wind saw continued growth into 2007.

3.2.4.2 CARICOM

The one (1) percentage point increase in RES use in Jamaica was due to the construction of the government owned wind farm in 2004. Since then, despite several invitations, there has not been any significant investment in RES for electricity[13]. The policy framework set out by the government provides for case by case assessment of potential projects. The current

[13] The government has decided to fund the expansion of the existing facility

monopoly by the utility also does not encourage this investment. This is further demonstrated by the fact that it required three years of negotiations between the utility company and the wind farm operators to agree on a feed-in tariff [36]. While there may be wind and water maps of the Island available, the technical impact of RES use is yet to be fully examined.

Table 3.1: Governmental RES Targets and Attainment Levels in 2000, 2004 and 2007

Country	Governmental Target for Renewable Use for Electricity Production – 2010 (%)	RES as a percentage of total electricity production 2000 (%)	RES as a percentage of total electricity production 2004 (%)	RES as a percentage of total electricity production 2007 (%)
Hungary	8	1	2.3	4.3
Poland	7.5	3	2.3	3.5
Bulgaria	11	7	8	8.4[14]
The Czech Republic	8	5	4	4.7
Jamaica	10	3	4	4
Trinidad	unspecified	0	0	NA[15]
St. Lucia	unspecified	0	0	NA
Guyana	unspecified	0	≈0.5	NA

The fact that Trinidad does not specify an RES target is a clear indication of its faith in the availability of its gas supplies. Given the market structure where the T&TEC provides the generators with gas supplies, it would be reasonable to expect that some of the costs associated with RES use would be borne by the company. Given that there is no fuel input for RES it stands to reason that the T&TEC would be required to fund infrastructure cost, which may be considered as not being feasible.

[14] The percentage achieved in 2005 exceeded the 2010 target. The total supplied was approximately 11.8%.

[15] Not available

To this extent it is clear that neither policy[16] nor market structure is geared towards greater use of RES. As the home of the engineering arm of the regional university, Trinidad is not short of the technical capacity to facilitate increased RES use.

While there was no target specified by the St Lucian authorities for electricity production, there was an undertaking, given by the Prime Minister at the 2000 climate conference in The Hague, to reduce greenhouse gas emissions by 35% by 2010 [37]. A part of this goal was a move to shift from the traditional production of electricity by diesel to wind and geothermal (of which the country has an abundant capacity). However, although provided with a firm offer to build a wind facility, the national utility company LUCELEC is yet to agree to its implementation. As in Jamaica the company is guaranteed a minimum return on its investment as well as the ability to operate on total cost recovery; to this end although agreeing to look at the project the company has made no effort to facilitate it becoming reality. It is also important to note that the governments objective is being met in RES heating and small independent PV electricity schemes.

With Hydro potential in excess of 7GW the Guyana government has consistently indicated its willingness to have this resource tapped to supply its domestic and potential export markets. While not however indicating a specific level of penetration, its policies have resulted in a number of memoranda of understanding being signed for investors to take advantage of the vast potential [26]. The market structure in which the Guyana Power and Light (GPL) operates facilitates interconnection from these generators.

It is clear that there has been steady growth in the use of RES-E within the EU countries highlighted. Notwithstanding the fact they may have been forced by the need to join the European Union, it has been clearly demonstrated that market structure supported by well formulated policies are excellent stimuli for the growth and development of the use of renewable energy.

Although not yet coming to fruition, it has been shown in the case of Guyana that a properly structured market, even in the absence of clear policy guidelines, can facilitate the growth and development in this area. On the other hand the St. Lucian experience clearly demonstrates that with the best will in the world, a trading monopoly can easily prove to be the death knell of governmental goals.

[16] As of 2009, a governmental committee has been formed to look at renewable energy use in Trinidad and Tobago

3.3 The International Scene

On January 31 2006, then President of the United States of America, George W. Bush, made one of the most profound statements regarding energy that may have ever emanated from that country. He said "*America is addicted to oil; the best way to break this addiction is through technology*". He further spoke to the resources above the US$10B already spent, to develop cleaner, cheaper and more reliable sources. These admissions/plans are quite remarkable, given his country's refusal to ratify the Kyoto agreement on greenhouse gases. It however helps to focus the minds of those involved in research regarding renewables, on finding solutions to the technical challenges affecting their widespread integration in existing systems. Additionally it is a clear indication that future development of any economy will rest on the use of renewables. Based on current statistics supplied by the Global Wind Energy Council (GWEC), USA has now topped the world in newly installed capacity.

Based on GWEC data the table below shows the installed wind capacity (MW) since the turn of the century. A cursory review of the table indicates that all the countries listed, with the exception of Jamaica, have very strong economies. It would also suggest that in order to maintain their dominance and to meet pollution targets, alternatives to fossil fuel plants was an imperative.

While the percentage of total load supplied by wind for a country such as the UK is relatively small, it must be noted that the increase to current levels has been aided, in part, to the introduction of the renewable obligations (Thomas, 2005). Suppliers are obliged to have a certain percentage of their demand supplied by power from renewable sources. The penalties applied for not meeting this target, ensure that these companies make it a priority to have such inputs. Ultimately this provides an incentive to generators who use renewables.

Table 3.2: International Installed Wind Capacity 2001 to 2008

Country	Cumulative Installed Capacity (MW)					
	2001	**2002**	**2003**	**2004**	**2007**	**2008**
Germany	8734	11968	14612	16649	22247	23903
Spain	3550	5043	6420	8263	15145	16754
USA	4245	4674	6361	6750	16824	25170
Denmark	2456	2880	3076	3083	3125	3180
India	1456	1702	2125	3000	7,845	9,645
Italy	700	806	922	1261	2,726	3,736
Netherlands	523	727	938	1081	1,747	2,225
Japan	357	486	761	991	1,528	1,880
UK	525	570	759	889	2,406	3,241
P.R. China	406	473	571	769	5,910	12,210
Jamaica	0	0	0	21	21	21

While not included in the table above, there was little or no growth in the Latin America and Caribbean region, except in Brazil and Mexico. The Caribbean saw no growth over the period. As one of the three largest Islands in the region, Jamaica must show leadership in helping to drive use of this technology. This however must be done with the support of meaningful research, hence the purpose of this study.

3.4 Previous Work Done in Renewable Energy in Jamaica

It is without question that work has been carried out in Jamaica regarding renewable energy use. The very fact that it forms part of the energy policies of 2006 and 2009 is testament that considerations have been given to this important aspect of the country's development.

The Petroleum Corporation of Jamaica (PCJ) is the organisation in Jamaica given the exclusive rights, through an extension of the Petroleum Act 1979, to explore and develop all renewable energy resources on and around the Island [38]. It is therefore to this organisation that this researcher has looked to determine the extent of the work done with respect to renewable energy use in electricity generation for the national grid.

Based on data obtained from the organisation, there are four renewable energy sources that have been explored on the Island. These Resources are namely; Solar, Hydro, Wind and Ocean Thermal Energy Conversion.

3.4.1.1 Solar

There are a number of small projects involving solar generated electricity across the Island. A total of approximately 300 kW of solar cells are installed across the Island. Much of this however is the result of the efforts of private individuals. While incentives exist for the use of the technology in households the cost of implementation remains prohibitive to the majority of Islanders.

The key are of solar technology use in concentrated in water heating. Expansion is the use for this purpose continues with the support of government backed low cost loans.

The other activities involving solar involves

1. Policy development with respect to taxation on related goods

2. Projects involving

    a. Grid-tie system for communities

    b. Stand alone systems for rural areas

    c. Implementation in local schools

3. Research in the development of solar farms

In summary solar PV technology is still in the early stages of development.

[19]

3.4.1.2 Hydro-Electricity

With respect to time of use, hydropower is by far the most mature renewable energy technology used on the Island for electricity production. The country's hydro electric capacity is based on run of the river systems and not on pumped or reservoir based systems.
There is a total installed capacity of 23.8 MW and potential capacity of 100 MW, scattered across the island. The fact that the most recently installed hydro facility was commissioned in 1989 is testament to the fact that benefits of the acknowledged potential capacity has not been fully explored.

[19]

3.4.1.3 Wind

Wind studies have been conducted across the island by the PCJ. In helping to meet the mandate of the energy policy, the organisation has constructed the first wind farm project. It will also be expanding the facility in the near future. While impact studies for the grid were conducted for this site, no comprehensive wind capacity studies have been conducted for the entire network.
There is also only now a wind map being developed for the island. Tracking of this necessary data have largely consequential from information garnered by meteorological office and private companies.

[19]

3.4.1.4 Ocean Thermal Energy Conversion

It is without question that the potential for this technology exists in the Caribbean. The PCJ has therefore determined that the implementation of a 10MW facility will be undertaken.

The challenge however with the technologies and efforts mentioned is that in none of the cases has the overall impact on the electricity grid determined. The information garnered from the PCJ indicates that the possibility of using these technologies rests in evidence of their benefits in other jurisdictions. It therefore makes it challenging to boldly specify how and where these technologies can be used within the grid, given that their local impact is largely unknown.

It is for this reason that this researcher believes that current policy documents are shrouded in very vague terms regarding renewable energy use. This is also true of the language used in the licenses associated with new generation for the grid. With such ambiguities, the attainment of the set targets will remain elusive.

[19]

Conclusion

Notwithstanding the fact that there are challenges associated with using renewable energy sources; when there are focussed initiatives to support their use, positive change can be realized.

Though forced by the need to join the European Union, the experience of the four countries highlighted has clearly demonstrated that market structure supported by well formulated policies are excellent stimuli for the growth and development of the use of renewable energy. Although the increases in the current level of RES use among the four countries varied, each country’s output was consistent with focus that was placed on the particular energy source.

The reverse was however true for the Caribbean nations under review in that there was no appreciable increase in RES use even for those that had related policies.

In the case of Guyana it has been shown that a properly structured market, even in the absence of clear policy guidelines, can facilitate the growth and development in this area. While this is true, the absence of a market/policy combination may be one of the reasons why the country’s RES use has remained stagnant amidst the vast amount of available resources.

On the other hand the St. Lucian experience clearly demonstrates that with the best will in the world, a trading monopoly can easily prove to be the death knell of governmental goals.

The Jamaican government having sought to highlight the possibilities associated with renewable energy by investing in wind generation, failed to provide either a clear policy regarding the RES technology or a supportive operating environment to facilitate its expansion. The current decision to forego privatisation of the sole wind generating facility after several months of inviting bids is a clear indication of the lack of attraction owing to the non-existence of a market or a clearly articulated policy.

With this in mind this research will provide support for the effective development of the policy framework to drive the use of embedded generators. Given the information presented in this and previous chapter, it is becomes most relevant to look at the methodologies to be adopted in realizing the earlier listed objectives.

CHAPTER 4

Research Methodology – The Transmission Network Model

Chapter four outlines the methodology adopted in conducting the study. The chapter looks at the Jamaican transmission network model and the considerations made, with respect to generation, transmission and load, in development of its most appropriate representation.

Introduction

The acceptability of this research is inextricably linked to the accuracy of the network model used. Given that operation of the existing network is being analyzed and the security applied to some data, by the operator, various mathematical and computing tools are used to develop the information into an accurate and useful form.

The veracity of the final model is therefore checked against known real-time information and acceptable limits. Notwithstanding, some assumptions will be made, which are clearly articulated throughout the chapter.

With the availability of various tools with which to complete the model, it is also important that the one selected provides options for expansion, greater rigour for future work.

In attempting to achieve the aims set out in chapter one, the summarized methodology for the model are as outlined below:

1. Identification of the technical measures to be used in assessing the operation of the network was conducted.

2. Identification and selection of suitable modelling software, which makes it possible to calculate operation criteria.

3. Identify and use a standardized network to assess the operational criteria that were identified.

4. Model the Jamaican transmission network, with key focus on
    a. Load dynamics
    b. Generator operation with respect to
        i. Despatch
        ii. Cost

5. Test the criteria against increasing load demand based on current forecasts

4.1 Assessment Criteria

4.1.1 Power System Operation

A power system is the combination of generating, transmitting and distributing electrical energy for consumption. Consumers of this electrical energy must be satisfied that the electricity being supplied is of a certain quality and at the best price possible. To this end, the providers of this electricity must ensure that it is produced at the lowest possible price and transmitted and distributed with the least amount of losses in meeting the load demand. Governments or policy makers through various provisions such as emissions will impact the objectives of the providers in such matters as the types of fuel used for generation.

Despatch of generation in Jamaica is based on a merit order system. Inclusive in the criteria for such despatch are: despatch generation

1. “in ascending order of the marginal cost in respect of any hour for the generation and delivery or transfer of electricity into the system to the extent allowed by transmission system operating constraints based on “equal Incremental Cost-System” principles”.

2. “as will in aggregate and after taking into account electricity delivered into or out of the System from or to other sources sufficient to match at all times (so far as possible in view of the availability of generation sets) demand forecast taking account of information provided by authorised electricity operators, together with an appropriate margin of reserve for security operation”

the attendant factors being:

a. forecast demand (including transmission losses and distribution losses);

b. economic and technical constraints from time to time imposed on the *System* or any part or parts thereof;

c. the dynamic operating characteristics of available *generation sets*; and

d. other matters provided for in the *Generation Code*.

In summary generators are despatched based on their availability and economic cost of their output.
The implication of these criteria is that the fuel type used will determine, in large measure, the generating unit that is used to supply the load at a particular point in time.

For the purpose of planning, the individual generator output will be determined by conducting a power flow study. This power flow study provides information, primarily, about the magnitude and angle at the system busbars. The two parameters provide a clear indication of the reactive and active power flows at the busbar. Acceptable performance with respect to voltage level is therefore established by the utility company.

The load demand on a power system will vary based on time of day, day of the week, monthly or seasonally. It is therefore the responsibility of the provider to determine the level of generation required to meet that load and provide the requisite operating margin. This operation being ideal assumes that all the equipment in the transmission system inclusive of generators, lines and transformers are in service and working properly. Should any component fail, it is expected that the system will remain stable.

A system contingency study is the mechanism used to assess the level of stability through the loss of critical components. This evaluation is done by removing one or more components in succession, which gives rise to N-1, N-2 etc contingencies. Operation outside of set criteria is regarded as violations. A high number of violations are an indication of low stability while stability increases with a reduction in the number of violations.

The capacity of power system equipment to carry the requisite load is of paramount importance. Equipment are sized based on the magnitude of the current they are expected to safely carry. Overloading can result in equipment failure and/or damage. The effect of this is a loss of supply. To this end it is of critical importance that the loading levels of all equipment are determined.

The magnitude of the fault current flowing in a section of the network is affected by the generating capacity within the network as well as the system loading. Circuit breakers are rated based on the maximum level of current that they are expected to interrupt. This current magnitude is determined in part by the fault level within a particular substation. The fault level is given as

$$F_L = \sqrt{3} \times I_{SC} \times V_{bus}\ (MVA)$$

Equation 4.1

Where "I_{SC}" (kA) is the three phase fault current at the bus and "V" (kV) the bus voltage. Given the aforementioned the following criteria are established for assessment of the network:

1. *Bus voltage levels* – established network criteria are $v \pm 5\%$
2. *Generation Costs*
3. *Fault Levels*
4. *System Loading*
5. *System Losses and*
6. *Contingencies*

4.3 Programme Selection

Given the general aims and objectives of this research, it was necessary to make an assessment based on the actual Jamaican network. However, before such an attempt is made; an appropriate programme had to be identified for its modelling. The key requirements of such a programme were:

1. Ease of use
2. Functionality
    i. Load flow analysis, inclusive of time step analysis
    ii. Fault analysis
    iii. Generation cost calculations

iv. Modelling and incorporation of embedded generators
v. Optimization analysis

3. Repeatability of system analyses

4. Cost and availability

Based on these criteria, modelling was done using three available packages, namely:

1. MATLAB
2. ERACS and
3. PowerWorld

4.3.1 The MATLAB Model

The MATLAB model was developed using the Power System Analysis Tool, (PSAT) developed by Dr. Federico Milano. At the time of developing this model, the original objective was to include the use of Multi-Agents using the Neural Network toolbox available in MATLAB. The fact that PSAT was still being fine-tuned by its developer and end users, and that the final model would require the simulation of over a hundred busbars; it was decided that its use was unnecessary for the required purpose of this study.

4.3.2 The ERACS Model

While it was possible to model the entire network and carry out certain functions using ERACS, key functional aspects were missing. These included optimal power flow, cost calculations and time step analysis. The programme was therefore not explored any further.

4.3.3 The PowerWorld Model

PowerWorld was chosen as the programme to conduct this study as it met all the criteria listed above. The effectiveness of the programme however, had to be determined before applying it to the Jamaican network. As such, use was made of an accurately simulated and widely accepted power system model. A model from the United Kingdom Generic Distribution System (UKGDS) was used. Although a distribution network, the voltages used were representative of the transmission voltage levels used in the Jamaican network and therefore considered appropriate.

4.3 Standardized network Assessment

4.3.1 UKGDS Network

The networks were developed as a joint project between academia and the local electricity industry in a bid to provide suitable networks for the creation and testing of innovative solutions towards meeting United Kingdom governmental 2010 objectives regarding embedded generation.

UKGDS networks are placed into High and Extra High voltage (HV and EHV) categories. These categories provided for the analysis of networks of varying complexity and maximum voltage levels. The network identified as EHV 5, pictured below, was used.

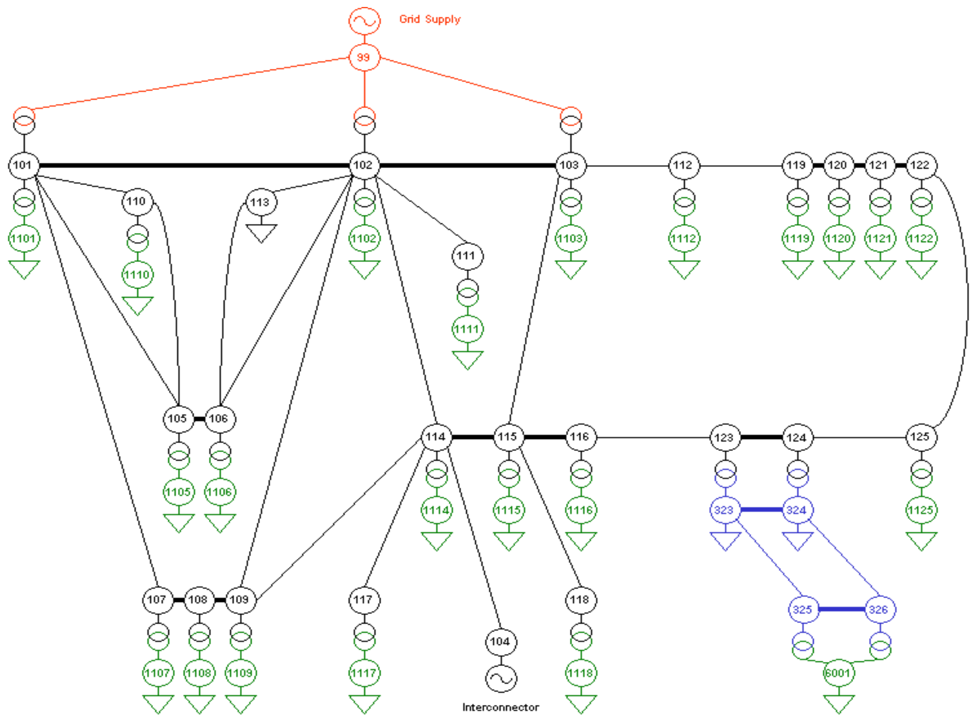

Figure 4.1: Extra High Voltage UKGDS network[17]

The Jamaican network consists of generation facilities concentrated at the south east and north western ends of the Island. The EHV5 network represents a similar generation concentration with the main grid supply point GSP supplying busbars 101-103, and an interconnection point at busbar 104. The maximum voltage in this system is 132 kV which

[17] Source Sustainable Electricity Distribution Group (SEDG)

is comparative to the 138 kV transmission voltage on Jamaica. The network also facilitated the inclusion of other generation facilities.

The EHV5 network is meshed and consists of fifty two (52) busbars of voltages ranging from 132 kV to 6.6 kV. The total maximum load on the network is 281.74 MW and 92.23 MVars, distributed among twenty five (25) load points. It is completed with thirty five (35) branches and twenty eight (28) transformers. The capacitance/reactance of some of the branches were adjusted, owing to the fact that they were a mix of cables and lines; this was done to reflect a predominantly line based model.

The load profiles associated with UKDGS, distinguish industrial and domestic loads from commercial loads. The classification for the three load types were made based on the overall power factor of the loads connected at prescribed busbars. The classification was based on the idea that domestic, commercial and industrial loads would operate at decreasing power factors respectively. The values used are shown in table 4.1:

Table 4.1: Load Classification Mechanism for the UKGDS Network

Classification	Industrial	Commercial	Domestic
Power Factor Range	pf<= 0.94	0.94<=pf<=0.96	pf>=0.96

These values are reflective of the values garnered from the feeder information supplied by the utility company. The final selection was made based on the “predominant” activity occurring in the areas specified. This however must not be taken as the actually power factor values measured for such load types in the network.

UKGDS Time Step Model

While the capacity of a system can be effectively tested by considering its operation at the extremes of maximum load with minimum and maximum generation as well as minimum load with maximum and minimum generation; its operation over time increments was necessary for this study. The impact of embedded sources having variable output with respect to the resource availability is best assessed over these increments. Analysis using this model was done using the twenty four hour (24 hr) load profile model associated with UKGDS. The profile is based on a typical percentage of the total maximum, in the specified category, in use at 30 minute intervals.

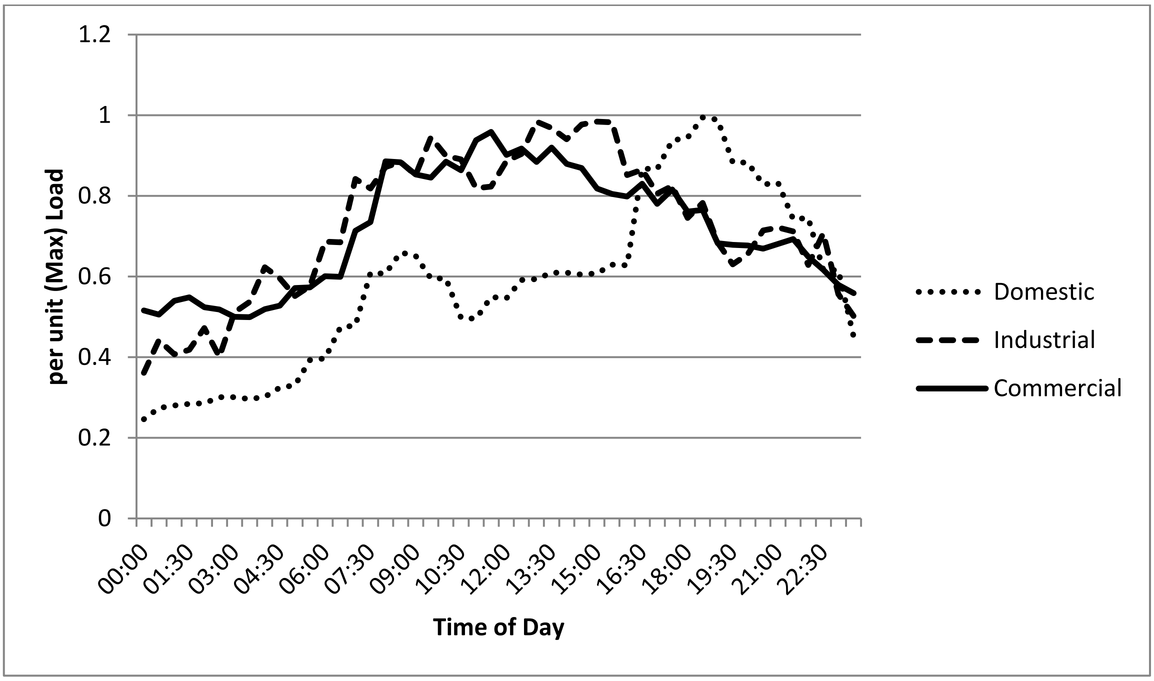

Figure 4.2: UKGDS Load Profile

Once classified, loads were then applied based on their respective profiles.

Generation Cost Model

The PowerWorld Application provides for the use of piecewise linear and cubic cost models. The cost function of the generator supply at the grid point was adjusted to represent the operation of a heavy fuel oil fired steam plant. An additional generator was included at a busbar to which a predominantly industrial load was connected to represent a CHP input. Together these represents the base case generation.

Cubic cost models were developed based on the fuel type and generator configuration, of the form:

$$C_i = AP_i^3 + BP_i^2 + CP_i + D$$

Equation 4.2

where A, B, C & D are constants; with D representing the fixed cost in \$/hr of operating the unit.

The cubic cost model was used given the unavailability of actual periodic generator output. The coefficients for the model were taken from a typical fossil fuel plant, provided in PowerWorld. The company from which the data was taken is Mirant Corporation, the same company owning the JPS at the start of this study. The overall cost of generation was therefore produced at each time step in the simulation and tabulated.

Fault Calculation

As part of the assessment of the impact of embedded generation, the effect on fault currents had to be considered. As such PowerWorld was assessed with respect to its fault calculation capacity. The simulation of symmetrical and unsymmetrical faults was conducted simultaneously on all busbars in the EHV5 UKGDS network.

Based on the fault analysis conducted on the network it was reaffirmed that the most severe were three phase faults occurring on those busbars containing generating units. Determination of the impact on fault currents from embedded generators at the appropriate busbar was therefore possible.

4.4 Jamaican Transmission Network Model

Busbars

The network representing the transmission system consists of voltage levels of 138 and 69 kV for transmission lines while Generator busbar voltages were set at 13.8, 11.5 and 6.9kV. The One Hundred and Seven (107) busbars are divided into four zones to facilitate switching[18]. Given that there is no trading, a single operational area was used. With the exception of the swing bus, all of the busbars are set to operate with a five percent (5%) tolerance.

Generators

A total of twenty eight generators are modelled, representing a total installed capacity of just below eight hundred megawatts, 800 MW. This consists of fossil fuel and hydro electric units. The fossil fuel units represent approximately Ninety Five percent (95%) of those modelled. Although included, generators associated with two manufacturing entities are not considered in any of the power flow models. The lone wind facility on the Island is not included in the base model. It is however included in the siting and capacity studies.

Generator Operation

All generators with the exception of the hydroelectric units are set to operate based on economic dispatch. MW and Mvar limits are set for each unit. The management of the output of individual units are however set based on their participation factor. Given the unavailability of the company's dispatch algorithm, participation factors were determined based on trial and error. Maximum active power outputs are set based on the capacity of the units while Var limits are set according to the values established by company data.
All sequence impedances are converted to represent the system base.

[18] Although the network was set up for load/generator switching, given that this data was unavailable from the company it was not included in the model. Load flow studies were therefore developed using economic dispatch.

Generator Cost Model

The data garnered from the utility company provided the heat rates as well as the variable cost per kWh and variable cost per kWh-yr, for each fossil fuel based type unit used within the network. The figures were based on the company's operation in 2006. Although individual units would operate based on their own efficiencies, the unavailability of data for each was overcome by assuming that similar units, with respect to fuel, operated based on the same data provided. The fossil fuel units within the network used, Heavy Fuel Oil (HFO) or Automotive Diesel Oil (ADO). ADO was used as the fuel for the medium speed diesel, combined cycle and combustion turbines. The data, as supplied by the JPSCo, for these units are shown in Table 4.2:

Table 4.2: Costs Associated with Generating Units on Jamaica in 2006

	Oil Fired Steam HFO	Combined Cycle (ADO)	Medium Speed Diesel (ADO)	Combustion Turbine (ADO)
Operations and Maintenance (O&M)				
Variable (US$/kWh)	0.006	0.005	0.011	0.01
Fixed (US$/kW-yr)	23	10.5	19	6

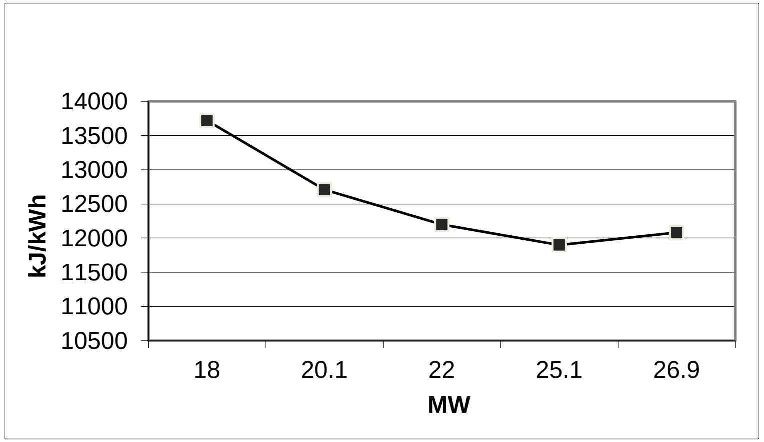

Figure 4.3: Heat Rate for Steam Unit (HFO)

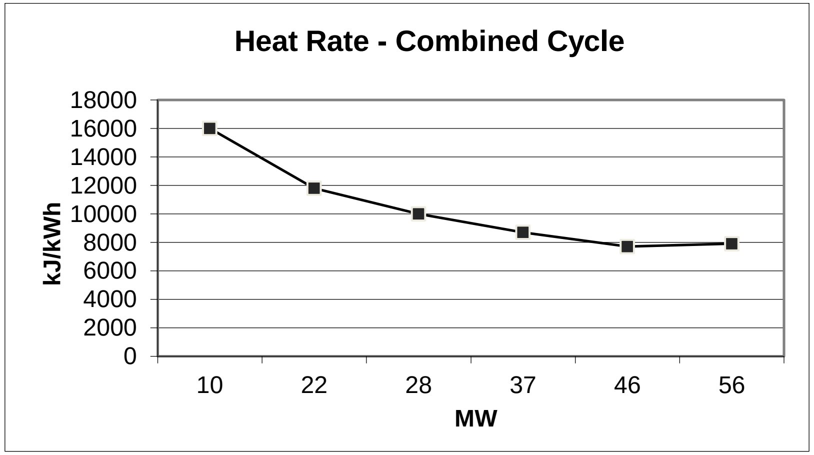

Figure 4.5: Heat Rate Combined Cycle Unit

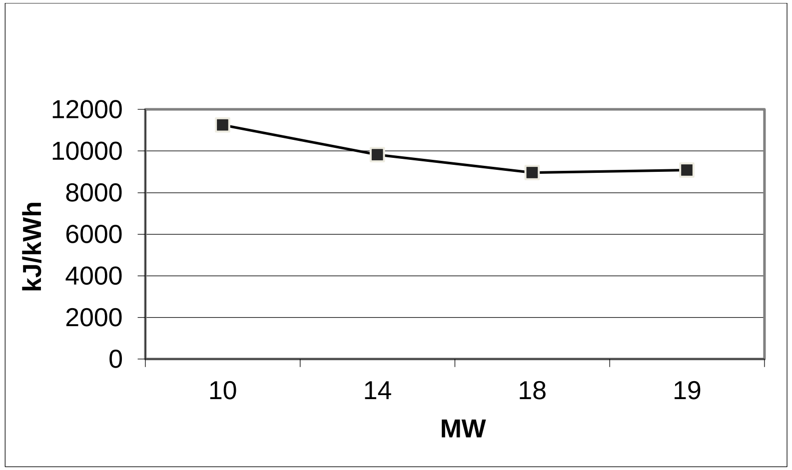

Figure 4.4: Heat Rate for Combustion Turbine Unit

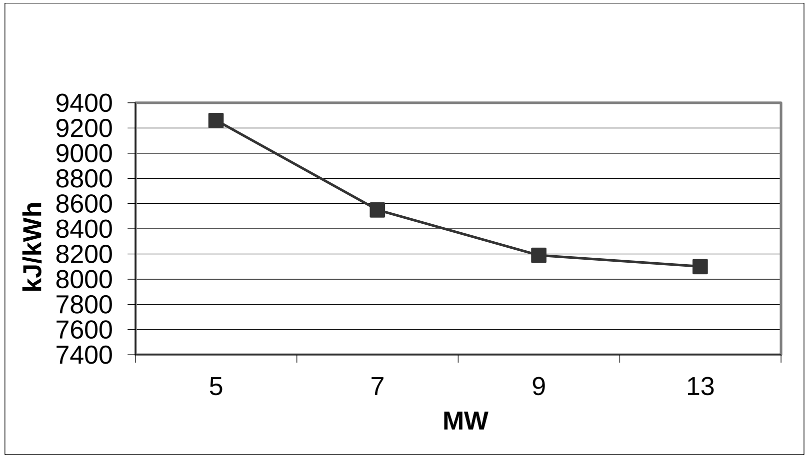

Figure 4.6: Heat Rate for Diesel Units

Table 4.3: Corresponding MWh and Operation and Maintenance Costs

	Oil Fired Steam HFO	Combined Cycle (ADO)	Medium Speed Diesel (ADO)	Combustion Turbine (ADO)
Operations and Maintenance (O&M)				
Variable (US$/**MWh**)	6	5	11	10
Fixed (US$/**MW-h**)	2.63	1.2	2.17	0.68

The appropriate data for input to PowerWorld was developed. The requisite calculation for the HFO unit is shown below:

Using the world market price of crude oil at the time of model construction:

HFO = $140/bbl

Given a calorific value of approximately 5.848 Mbtu/bbl the unit's fixed fuel cost is given by

$$\boldsymbol{fixed\ fuel\ cost = \frac{cost\ per\ bbl\ of\ oil}{calorific\ value} = \frac{140}{5.8480314} \approx 23.94\ \$/MBtu}$$

The heat rate and cost associated with the HFO steam unit and the corresponding derived quantities are shown in table 2.7

Using the Curve Fitting Tool (cftool) in MATLAB, the coefficients of the unit's cost curve was determined at a ninety five percent (95%) confidence level.

Table 4.4: Operational Parameters for HFO Steam Generating Unit

Output (MW)	Heat Rate (kJ/kWh)	Heat Rate (MJ/h)	Heat Rate Mbtu/h) (*.000947817078)	Cost ($/h) (*fixed fuel cost)
18	13720	246960	234.0729	5603.630442
20	12710	255471	242.1398	5796.748756
22	12200	268400	254.3941	6090.113422
25	11900	298690	283.1035	6777.406774
27	12080	324952	307.9951	7373.303043

From the best fitting curve, the quadratic cost equation was determined as

$$\boldsymbol{C}\ (\$/\boldsymbol{h}) = \ \mathbf{14.77}\boldsymbol{P}^{\mathbf{2}}\ -\ \mathbf{468.2}\boldsymbol{P} + \mathbf{9247}$$

The corresponding incremental fuel costs “λ” were therefore determined from

$$\boldsymbol{\lambda} = \mathbf{29.54}\boldsymbol{P} - \mathbf{468}$$

The values were then interpolated to derive input values up to 30 MW.

The corresponding heat rate curve was also determined using the method outlined above. This resulted in a quadratic equation

$$\boldsymbol{H}\ (\boldsymbol{MBtu}/\boldsymbol{h}) = \ \mathbf{1.023}\boldsymbol{P}^{\mathbf{2}}\ - \mathbf{39.26}\boldsymbol{P} + \mathbf{613.9}$$

The cost and heat rate values derived from measured and calculated costs are shown below in Table 4.5.

Table 4.5: Comparison of the Measured and Calculated Generator Cost and Heat Rate

Generator Output	Measured cost ($/h)	Calculated Cost ($/h)	Measured Heat Rate (Mbtu/h)	Calculated Heat Rate (Mbtu/h)
18	5603.63	5604.88	234.07	232.74
20	5796.75	5803.41	242.14	249.18
22	6090.11	6095.28	254.39	247.80
25	6777.41	6800.43	283.10	261.26
27	7373.30	7340.14	308.00	304.54

The quadratic functions for the remaining units are

Automotive Diesel Oil Combined Cycle (ADOCC)

$$\boldsymbol{C}\ (\$/\boldsymbol{h}) = -\mathbf{0.2546}\boldsymbol{P}^{\mathbf{2}} + \mathbf{216.1}\boldsymbol{P} + \mathbf{3880}$$

with a corresponding heat rate of

$$\boldsymbol{H}\ (\boldsymbol{MBtu}/\boldsymbol{h}) = -\mathbf{0.006829}\boldsymbol{P}^{\mathbf{2}} + \mathbf{5.796}\boldsymbol{P} + \mathbf{104.1}$$

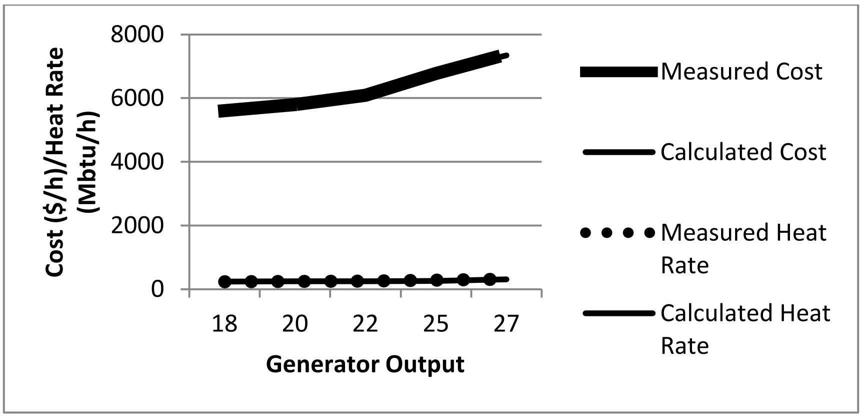

Figure 4.7: Graphical Comparison of Generator Calculated and Measured Cost and Heat Rates

Automotive Diesel Oil Combustion Turbine (ADOCT)

$$\boldsymbol{C}\ (\$/\boldsymbol{h}) = \mathbf{3.593}\boldsymbol{P}^{\mathbf{2}} + \mathbf{124}\boldsymbol{P} + \mathbf{2386}$$

with a corresponding heat rate of

$$\boldsymbol{H}\ (\boldsymbol{MBtu/h}) = \mathbf{0.09637}\boldsymbol{P}^{\mathbf{2}} + \mathbf{3.325}\boldsymbol{P} + \mathbf{63.98}$$

Automotive Diesel Oil, Medium Speed Diesel (ADOD)

$$\boldsymbol{C}\ (\$/\boldsymbol{h}) = \mathbf{4.321}\boldsymbol{P}^{\mathbf{2}} + \mathbf{182.4}\boldsymbol{P} + \mathbf{619.2}$$

with a corresponding heat rate of

$$\boldsymbol{H}\ (\boldsymbol{MBtu/h}) = \mathbf{0.1159}\boldsymbol{P}^{\mathbf{2}} + \mathbf{4.891}\boldsymbol{P} + \mathbf{16.61}$$

Transmission Branches

The entire system consisted of overhead transmission lines. The data used was based on system information as of 2006. Lines built after were not considered. The MVA limits ranged from Three Hundred and Forty (340) to Seven Hundred and Ninety (790). On average however, the loading limit was 450 MVA.
Transmission line transposition was not independently entered into the model, as the effect was assumed to be negligible.

Transformers

The transformers modelled in the network were inter-bus or generator units. Of the Forty Two units, there are Twenty Eight (28) generator and fourteen inter bus (14). The configurations used included Grounded star (Wye) – Delta, Wye-Delta and Delta-Delta. A breakdown of these configurations is shown below:

Table 4.6: Transformer Configurations used in the Jamaican Network

Configuration	Number	Comment
Delta – Delta	2	Small Hydro Plants
Wye – Delta	6	Small Hydro plants and Hunts Bay Gas Turbines
Grounded Wye – Delta	34	Other Units

The available data from the company for each transformer were:

i. MVA rating
ii. Primary and Secondary Voltages
iii. Winding configuration
iv. Phase shift
v. Positive and zero sequence
vi. Positive and zero X/R ratios
vii. Tolerance
viii. Number of taps

The input data was therefore determined as illustrated by the following example:

Bogue Inter-Bus Transformer					
From bus ID	Bogue_138	R_{grd} Primary (pu)	0.000	Tolerance [%]	1.00
To bus ID	Bogue_69	X_{grd} Primary (pu)	0.000	Min. Prim. Tap ex.	68.31
MVA	100	R_{grd} Secondary (pu)	0.000	Max. Prim. Tap ex.	69.69
Primary kV	138	X_{grd} Secondary (pu)	0.000	Number of taps	10
Secondary kV	69	Z1 (pu)	0.1190	Loading lim. Std.	80.00
Primary winding	“Y”-Grounded	Z0 (pu)	0.1190	Loading lim. Emer.	120.00
Secondary winding	Delta	X/R POS	32.000	Control bus ID	Bogue
Phase Shift	-30	X/R ZERO	32.000	Control bus volt.	69.00

The data required for PowerWorld are the per unit resistance and reactance hence

Equation 4.3

$$Z = \sqrt{R^2 + X^2} \text{ where}$$

$$\frac{X}{R} = 32 \text{ hence}$$

$$X = 32R \text{ substituting we have}$$

$$Z^2 = R^2 + (32R)^2$$

$$Z^2 = R^2 + \left(\frac{X}{R}\right)^2 R^2$$

$$\Rightarrow R = \sqrt{\frac{Z^2}{\left(1 + \left(\frac{X}{R}\right)^2\right)}}$$

From these equations the resistive and reactive values for this unit are 0.003399 and 0.118951pu respectively. Given that the transformer rating and the base MVA were equal at 100, there was no need to adjust the values; however consideration had to be given to instances where a difference existed.

For the taps associated with the unit, the 1% was applied at equal 20% intervals about the nominal voltage. The remaining information was inputted as required.

Load Model

As a critical part of its operation, the utility company only provided feeder load data at six time points. The times provided were **04:00; 08:00; 11:00; 15:00; 19:00 and 22:00**. It was therefore necessary to develop a daily load profile at half hourly intervals for each substation. Given that there are no formulae to determine the load demand at prescribed times; the time steps were determined using linear interpolation.

The function used was:

$$\boldsymbol{yi = interp1(x, y, xi)}$$

Equation 4.4

Where vectors “x” and “y” are the original data supplied by the company and “xi” and “yi” are the vectors at the twenty four (24) hour time points. The data supplied and generated for a feeder on the system is shown below. As indicated above, there is no exact science for determining the load at a given point, hence the visual comparison was considered satisfactory.

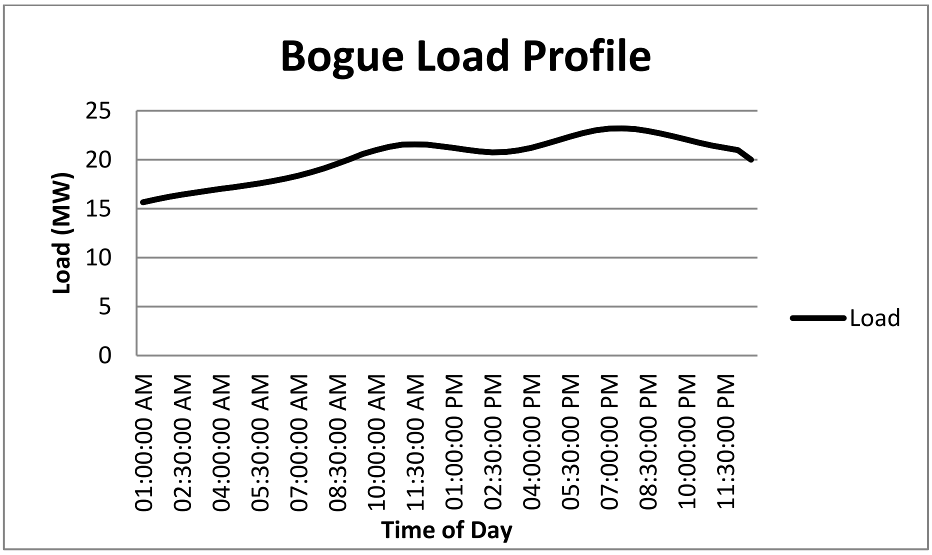

Figure 4.8: Load Profile for the Bogue Feeder from Interpolated Data

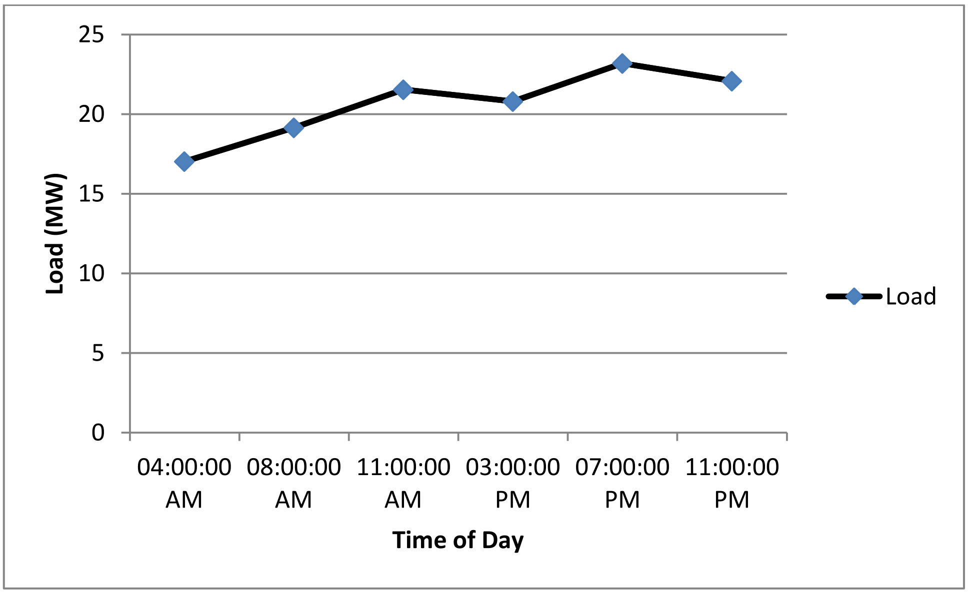

Figure 4.9: Load Profile for the Bogue Feeder from Company supplied Data

Whereas the data was separated into domestic, industrial and commercial loads strictly on the basis of power factor in UKGDS network, there was no such application for the actual network. The individual and overall demand was based on the actual feeder data supplied, which would have considered the full mix of load types.

Losses

Based on company data, the 22.9% losses occurring on the network is broken down as shown in table 4.7.

Table 4.7: Network losses as a percentage of system output

Transmission Network	3.5
Primary Distribution Lines	1.3
Distribution Transformers	1.2
Secondary Distribution Lines	4
Non-Technical Losses[19]	12.9

[21]

This corresponds to type of losses being as highlighted by figure 4.10

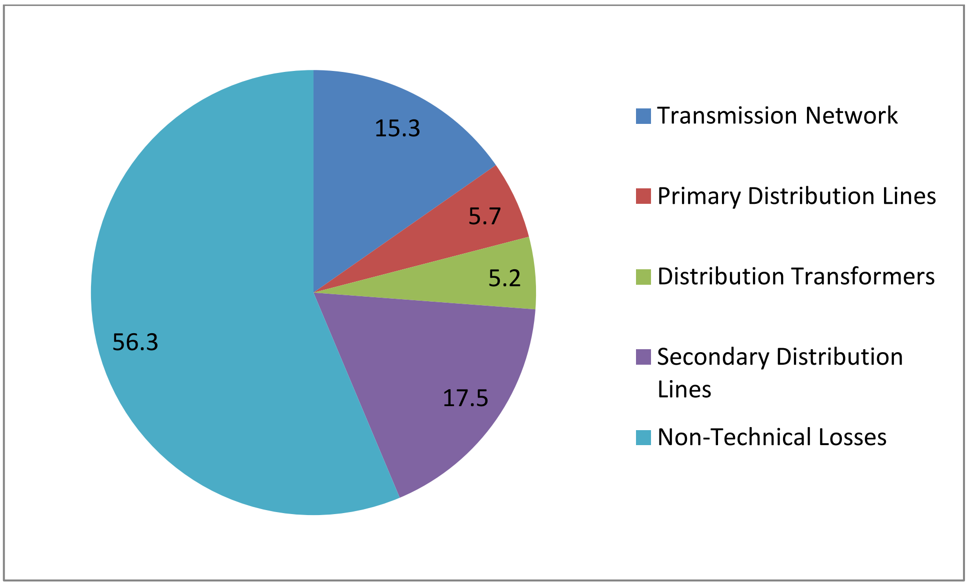

Figure 4.10: Type of Network Loss as a Percentage of Total Losses

The demand for the feeders is the sum of:

i. The actual load demand

[19] Non-technical losses are generally the result of theft of electricity which is quite widespread on the Island

ii. Distribution losses inclusive of lines and transformers and

iii. Non-technical losses.

The network model therefore provides data for only the transmission network.

4.5 Model Validation

Generation dispatch algorithm or operation is a function of load conditions, unit availability, operation costs (marginal cost), system congestion as well as company and national policies. Not having all these data in real time, the following fundamental operating conditions were assumed:

1. All Hydro Plants were running at full capacity
2. All company owned steam plants were running
3. Given that the maximum load is being serviced, all private power partners were in operation
4. The "participation factor" for each unit was set based on its maximum output[20]
5. Cost model for the private power companies were taken to be similar to that of the utility company based on fuel type.[21]
6. The Cost model for hydro plants were set at the lowest independent fuel cost value for the fossil units and an operational and maintenance cost of $6/hour
7. Hydro plants were assumed to have a fixed MW and MVar output; thereby not contributing to Automatic voltage regulation[22]
8. MW and MVar limits were adhered to throughout the study
9. MVar ratings on shunt capacitors were set to continuous thereby allowing them to adjust to the output level required to meet the desired voltage level.
10. All spinning generating units were set to operate on economic dispatch[23]

Verification of satisfactory operation of the network was based on:

[20] Participation factors are used to determine how AGC (automatic generation control) generators participate in driving area control error (the difference between the scheduled and actual power) towards zero.
[21] It is generally assumed that the operational efficiencies of the private power plant operators are better than that of the utility company
[22] It is understood that seasonal variation occurs for run of the river hydro plants; this is however not considered for the maximum load study.
[23] This ensured that based on the participation factor and the controlled buses, generators within a certain area all operated at the same incremental fuel cost.

1. All load bus voltages falling within the five percent 5% tolerance band of the company

2. Technical losses are within the 2.2% range as stipulated in the Jamaica Energy Policy analysis 2005.

3. Congestion was minimized and or eliminated by ensuring that transmission equipment were not severely overloaded

4. The final system could operate on N-1 contingency criterion

4.5.1 Bus Voltages

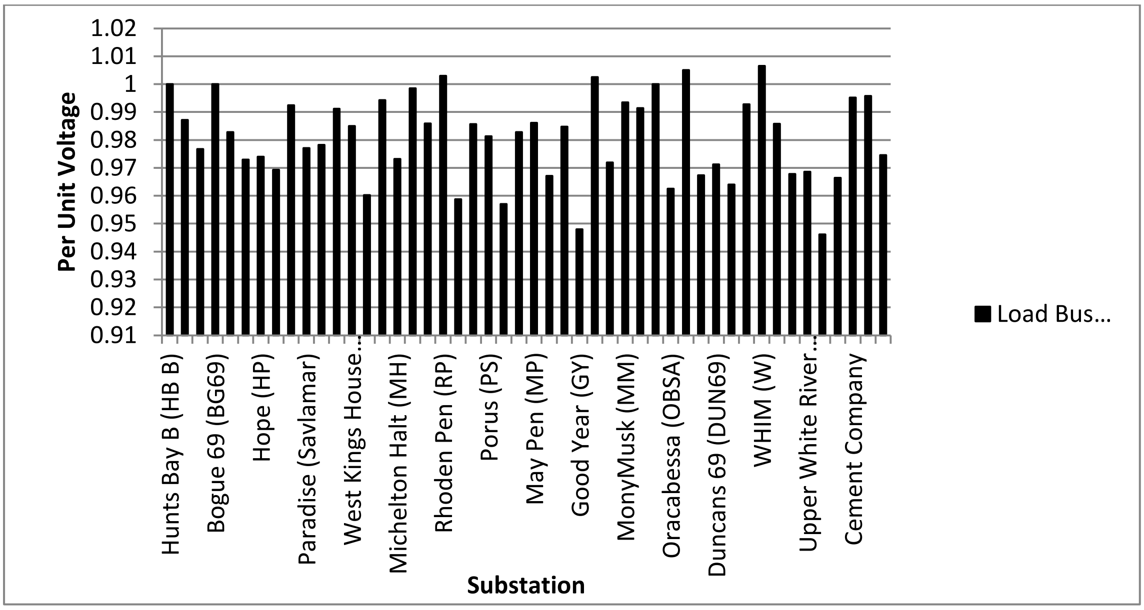

Figure 4.11: System Per Unit Load Bus Voltages

From Figure 4.11 shown above, the system load bus voltages range from a low of 0.945 per unit to a high of 1.006 per unit. Although the voltage was below the tolerance value, it was considered acceptable owing to the fact that only one two of the 48 buses had this voltage level.

Although not significant, there were greater number and more egregious tolerance violations in the generator bus voltages. However a key observation is the fact that where there were violations at individual generator busbars, the controlled buses associated with the station were at unity.

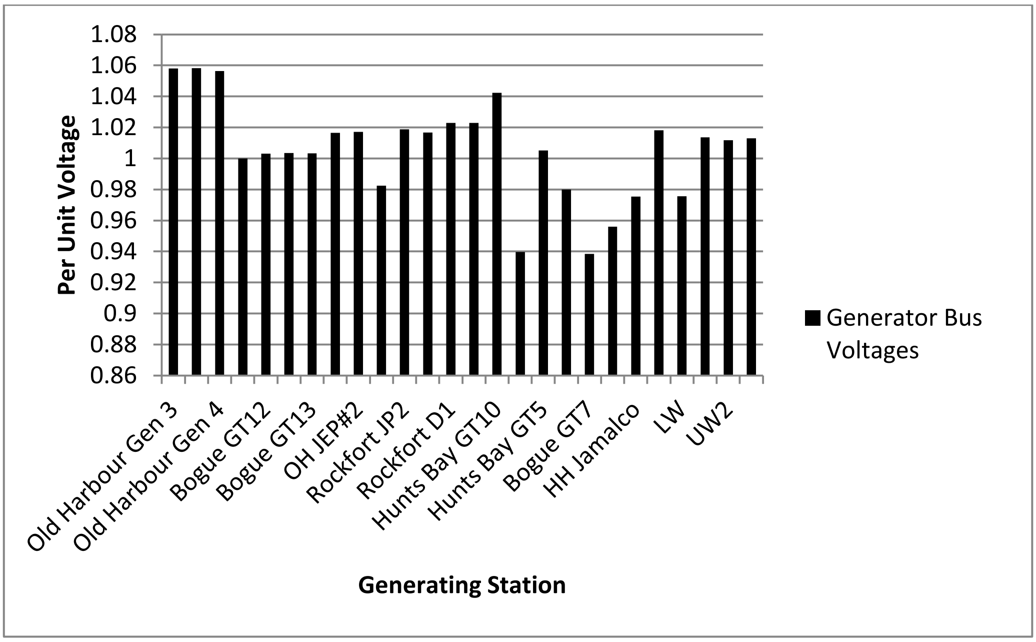

Figure 4.12: System per Unit Generator Bus Voltages

This indicates that the control mechanisms such as Automatic Voltage Regulation (AVR) and Automatic Generator Control (AGC) for the generators as well as tap-changing for the transformers are operating correctly.

4.5.2 Transformer Loading

Approximately seventy six percent (76%) of the transformers were operating below capacity and within the 80 loading limit as prescribed by the utility company. The average percentage loading on the transformers is sixty eight percent (68%), indicating adequate capacity for increased load. All except one of the units operating above 90% are associated with the hydro electric plants.

This was expected as each hydro plant was set to operate at peak or peak output, as outlined earlier. The Tredegar park unit, loaded at 104% results from inaccurate load sharing. The actual system consists of each transformer serving different components of the total substation load as against the single bus system used in the model.

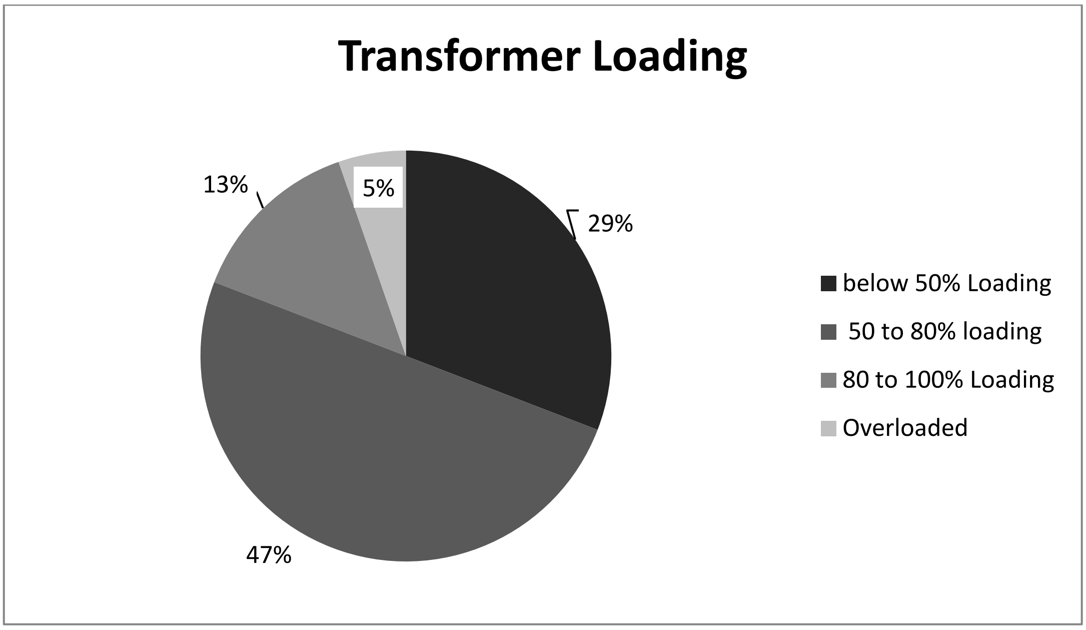

Figure 4.13: Transformer Loading

4.5.3 Transmission Line Loading

With line capacities ranging from 220 to 790 MVA and a total system load of approximately 620 MW, it is not surprising that the percentage loading on the transmission lines, range from a low of 0.4% to a high of 12.6%. The most heavily loaded line is used to import power into the corporate area from the Old Harbour generating plant.

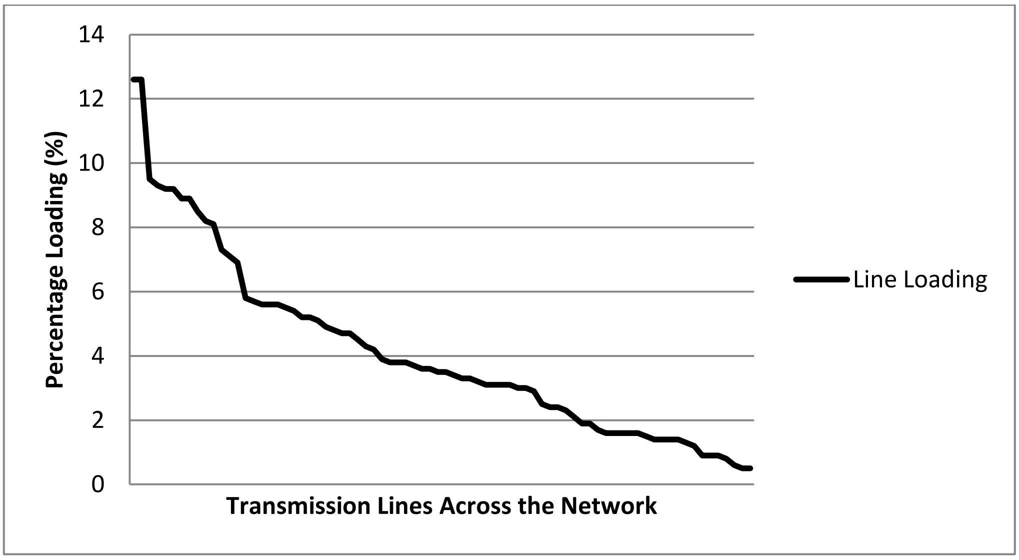

Figure 4.14: Percentage Range for Transmission Line Loading

It would have been expected that a study looking at the impact of increased generation from renewables or otherwise, would consider the overall stability of the network. However in reviewing the data for the line and transformer loadings as well as the bus voltages, it was not considered necessary. Given the busbar voltages and their significant deviation from unity it could be argued that the heavy loading of the system would warrant such a study. However when the extremely light of the transmission lines are considered such a instability issues were not considered to be a major factor.

Table 4.8: Per Unit Bus Voltages for Some Lines when supplying 2008 Demand

From PU Volt	From Bus Number	From Name	To PU Volt	To Bus Number	To Name
0.96	82	Rio Bueno (RB)	0.95	15	Cardiff Hall (CH)
1	34	Hunts Bay B (HB4)	1	32	Hunts Bay A (HB A)
0.98	14	Cane River (CR)	1	123	Cement Company
0.97	30	Hope (HP)	0.98	14	Cane River (CR)
0.95	26	Good Year (GY)	0.98	14	Cane River (CR)
0.99	23	Duncans 138 (DUN138)	1	5	Bogue 138 (BG138)
0.97	3	Bellevue 69 (BEL69)	0.97	4	Blackstonedge (BDG)
1	102	WHIM (W)	0.99	81	Rhoden Pen (RP)
0.96	85	Rose Hall (RH)	0.96	27	Green Wood (GW)
0.96	27	Green Wood (GW)	0.96	56	Martha Brae (MB)
0.98	76	Parnassus 69 (PN69)	0.98	126	Halse Hall
1	28	Greenwich Road (GR)	1	32	Hunts Bay A (HB A)
1	28	Greenwich Road (GR)	1	84	Rockfort (RF)

Table 4.9: Per Unit Voltages for Some Transformers Associated with the Lines in Table 4.8

From PU Volt	From Bus Number	From Name	To PU Volt	To Bus Number	To Name
1	75	Parnassus 138 (PN138)	0.98	76	Parnassus 69 (PN69)
0.98	2	Bellevue 138 (BEL138)	0.97	3	Bellevue 69 (BEL69)
0.96	82	Rio Bueno (RB)	1.01	19	RBB
0.99	47	Kendal 138 (KEN138)	0.98	48	Kendal 69 (KEN69)

While the bus voltages have fallen, a closer analysis shows that the voltage across each line was relatively the same; as shown by the examples of the bus to bus voltages for the lines in table 4.8. When compared with the data in table 4.9, it can be seen that the reduction in bus voltages occurred as a result of loading of the transformers. This is an acknowledged issue with the utility which has replaced several units in recent years.

4.5.4 Shunt Capacitance

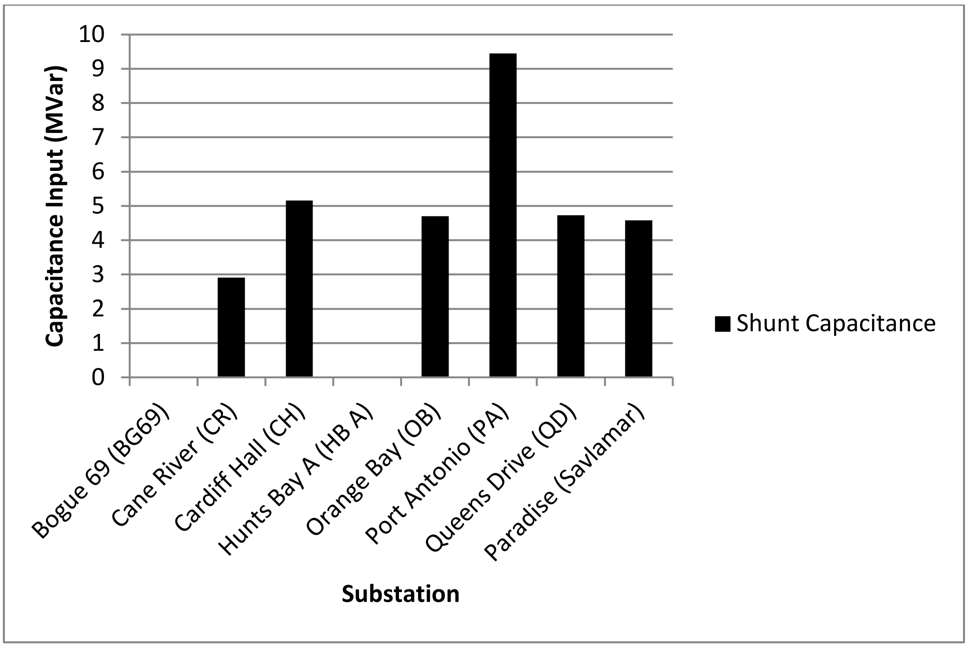

Figure 4.15: Switched Shunt Capacitance

Although all shunt capacitors were set to operate continuously, all final values were within the limits available for the network. At these values acceptable bus voltages were established.

4.5.5 Generator Output

Table 4.10 highlights the capacity of each online unit as well as the actual MW and MVar outputs. The data shows that none of the units are operating above their capacities. Also included are the available capacities from offline units. Based on the total generating capacity of, Seven Hundred and Sixty Two Mega Watts (762 MW), which is online, the hot spinning reserve is approximately 129MW. This represents a 20.4% operating margin.

Table 4.10: Generator Capacities and Output

Generator	Generator Output (MVA)	Generator Output MW	Generator Capacity (MW)	Generator Reactive Power Output (MVar)	Generator Capacity (MVar)
Old Harbour Gen 3	68.88	62	63.5	30	42
Old Harbour Gen2	64.41	57	58.5	30	45
Old Harbour Gen 4	55.02	46.12	65.1	30	60
Hunts Bay B6	44.25	44.25	65.1	0.07	42
Old Harbour Gen 1	31.75	31.35	38	5	16
OH JEP#1	36	36	37.08	0	30
OH JEP#2	32	32	33.91	0	30
Rockfort JP2	29.76	28.35	30.6	9.06	22.5
Rockfort JP	29.47	28.35	30.6	8.06	20
Hunts Bay GT10	24.66	17.48	32	17.4	21
Bogue GT9	17.5	17.44	25	1.44	16.89
Hunts Bay GT5	22.06	11.37	21.5	18.91	24.5
Hunts Bay GT4	16.24	11.37	21.5	11.6	14
Bogue GT7	10.01	9.94	19.87	1.19	14
Bogue GT8	12.06	9.94	19.87	6.82	80
Rockfort D2	19.94	19	20	6.04	15
Rockfort D1	19.94	19	20	6.04	15
Bogue GT12	40.91	40.85	43	2.27	26.65
Bogue GT13	40.91	40.85	43	2.27	26.65
HH Jamalco	10.3	9	10	5	5
Bogue ST	40.91	40.85	43	2.27	26.65
MG2	7.41	5.93	6	4.45	4.5
LW	4.63	4.52	4.52	1	1
Roaring River 6.9	5	4	4.05	3	3
UW2	4.24	3.39	3.39	2.54	2.54
RBB	2.94	2.35	2.49	1.76	1.76
Bogue GT 11	0	0	25	0	29.61
Bogue GT6	0	0	20	0	80
Bogue GT3	0	0	22.74	0	13.8

4.5.6 Generation Cost

Table 4.11: Generator Costs

Generator	Generator Production Cost ($/h)	Incremental Cost ($/MWh)
Old Harbour Gen 3	41006.9	418.17
Old Harbour Gen2	38916	418.17
Old Harbour Gen 4	34394.9	418.17
Hunts Bay B6	33581.9	418.17
Old Harbour Gen 1	28189.7	418.17
OH JEP#1	12774.9	441.7
OH JEP#2	11008	441.7
Rockfort JP2	9467.08	398.48
Rockfort JP	9467.08	398.48
Hunts Bay GT10	7926.31	231.81
Bogue GT9	7916.95	231.81
Hunts Bay GT5	6640.17	195.85
Hunts Bay GT4	6640.17	195.85
Bogue GT7	6362.33	159.93
Bogue GT8	6362.33	159.93
Rockfort D2	6207.88	337.98
Rockfort D1	6207.88	337.98
Bogue GT12	5144.2	145.46
Bogue GT13	5144.2	145.46
HH Jamalco	2677.84	159.92
Bogue ST	1379.36	39.01
MG2	105.28	6
LW	96.82	6
Roaring River 6.9	93.7	6
UW2	90.04	6
RBB	83.8	6
Bogue GT 11	0	0
Bogue GT6	0	0
Bogue GT3	0	0

The table above shows the actual production cost and incremental cost for each generating unit.

4.5.7 Load Growth

According to Jamaica Public Service data, average peak load demand increased by 2.4% in the last ten years, ending 2008, and 1.1% over the last five. During the same period, the average demand grew by 3.7% and 2.2% respectively. The Economic Commission for Latin America and the Caribbean (ECLAC) 2005 report "**Renewable Energies Potential in Jamaica**", indicates that the growth rate in the country has been haphazard, at best, during the period 2000 to 2004. The report cites the years 2000 and 2002 where load demand grew by 11.8 and 1.7% respectively.

The 2006 Jamaica Energy Policy, estimates medium term load growth of 3 to 4%. The office of Utilities regulation has also provided its own estimate regarding peak demand as shown in Table 4.12:

Table 4.12: Estimated Percentage Increase in Peak Load 2002 – 2020

Year	**Estimated Peak Demand (MW)**	**Percentage Increase**	**Year**	**Estimated Peak Demand (MW)**	**Percentage Increase**
2002	563.9		**2012**	871.9	*4.48*
2003	590	*4.63*	**2013**	911.1	*4.50*
2004	614	*4.07*	**2014**	952.1	*4.50*
2005	641.9	*4.54*	**2015**	995.3	*4.54*
2006	670.8	*4.50*	**2016**	1040.5	*4.54*
2007	700.8	*4.47*	**2017**	1088.1	*4.57*
2008	732.1	*4.47*	**2018**	1138.2	*4.60*
2009	764.7	*4.45*	**2019**	1190.8	*4.62*
2010	798.9	*4.47*	**2020**	1246.3	*4.66*
2011	834.5	*4.46*			

The table reflects an average increase of 4.5% per annum.

These estimates and the actual growth stipulated by the JPSCo further highlights the unpredictability of the electricity demand on the Island. It is therefore believed that an estimate of 2.5% annual growth going forward is reasonable for the purpose of this research. This increase is therefore reflected in both peak and time point analyses.

Using this annual growth rate peak demand from the present through to 2020; peak demand forecast are as shown table 4.13:

Table 4.13: Estimated Peak Demand at 2.5% Growth

Year	Estimated Peak Demand (MW)
2008	620.0
2009	635.5
2010	651.4
2011	667.7
2012	684.4
2013	701.5
2014	719.0
2015	737.0
2016	755.4
2017	774.3
2018	793.7
2019	813.5
2020	833.8

4.5.8 Contingency Studies

Contingency studies were conducted separately for Transmission Lines, Transformers and Generators. The resulting violations provide, in part, a basis for determining the robustness of the network. Violations were considered based on the frequency of occurrence with specific pieces of equipment, as well as the increases in equipment loading.

4.5.9 Fault Levels

The system fault levels provide the basis in determining the level of reinforcement required for the network with the inclusion of renewable sources. Increased fault levels represent the need for network reinforcement. The fault levels measured in MVA is determined by first conducting the fault study on the busbar in question. The resulting current is then used to determine the fault level using ***equation 4.1***

Conclusion

We have now established the specifics regarding the modelling of the transmission network. The key areas of focus in completing the model were the actual physical components, the load dynamics and the operating costs for the generators. The chapter concludes by outlining the bases on which the operational acceptability of the network will be determined. The determination of the wind resource is now considered.

CHAPTER 5

Research Methodology – Wind Modelling and Analysis

Chapter five outlines the methodology adopted in conducting the study of the Island's wind pattern. The cost of operation for a wind farm facility as well its modelling is covered. The chapter ends by reviewing the process of selection for the generator technology and the actual generator used.

Introduction

At the core of this research is the analysis of the impact of renewable energy source generators embedded into the existing network.
It is therefore critical to use wind data that is credible and representative of the general prevailing local conditions.
Without the benefit of a wind map for the Island, use is made of the available wind information. Given that the wind information available was not gathered for the purpose being undertaken, it will require processing to make it suitable. The wind data is therefore analyzed to determine its daily, monthly and seasonal variations as well as the relationship between data samples taken from different sections of the Country. Once established the information is then processed into a useable resource for electricity generation.

Selection of the appropriate wind turbine technology and ultimately selection of a suitable unit is also considered. The modelling and ultimate estimated capital and operational cost for a wind farm is also considered. To undertake these tasks the methodology adopted in assessing the impact of wind generation systems is set out in the following sequence of activities:

1. Analyze the wind patterns across the island using statistical measures

2. Generate wind profiles for different sections of the island and at different times of the year

3. Assess electrical output for different generators and select the most appropriate turbine

4. Develop costing mechanism for wind generated electricity

5. Develop a method for measuring green house gas production

6. Inject wind farm output into the areas of the island already identified for such and reassess the criteria as set out in section 4.1.

7. Determine which site provides the greatest benefit identified in item “10”

5.1 Wind Pattern Analysis

5.1.1 Wind Resource

The use of wind energy would not be considered if there was not a perceived availability of sufficient wind to make the operation viable. Anecdotal evidence of the prospects of harnessing this resource and its inclusion in an electric power system is insufficient. Given the key objectives of this study it was necessary to properly identify the potential power output of wind in Jamaica. Although wind is a random quantity, a reasonable and general pattern of its availability can be identified when viewed over a longer period of time [22]. The Wind spectrum, when considering wind variations, demonstrates the fact that the wind resource is best described when assessed over longer periods of time [39]. *E.L. Petersen et. al. – "Wind power Meteorology Part II, Siting and Models"*; supports the view that the average annual power production from wind has a relatively small standard deviation. In other words, when assessed over many years the uncertainty or inconsistency of the wind as a power production resource diminishes significantly. It therefore means that before deciding to use such a resource, copious amount of wind data collected over many years are required.

Given the above established requirement, there is a fundamental challenge to this Jamaica based study. The only available wind data were derived from coastal and inland measurements made over a five year period, which is considered short. It was however necessary to use this available data to develop a wind model that could fulfil the needs of a meaningful study of the potential impact of wind power in the power system.

To achieve this goal, it was necessary to first establish:

1. If there were in general daily, monthly, seasonal and annual patterns to the wind resource

2. The extent to which the wind varies in accordance with the location from which measurements were taken

The tasks thereafter were to:

1. Identify the technical characteristics of the wind
2. Replicate, within reason, a suitable wind resource and
3. Validate the generated wind data by comparing it to the available data.

5.1.2 Wind Patterns

Wind being a random quantity varies with time, location and other physical factors such as height. Wind, when considered as a heat driven quantity, helps to bring further clarity to its unpredictability. Owing to the mild changes that occur in the general weather/climate on the Island the actual impact of temperature on wind was determined. In order to establish the need for further research, the average measure of the wind resource was first made for the periods mentioned above, namely daily, monthly, seasonally and annually for the periods for which data was available.
Analysis of these data was facilitated using the Windographer software package. The specific areas for which data was collected are shown on the country map in Figure 5.1.

The wind data used for this study was not collected for the purpose of power generation. Readings were therefore done at heights less than what would be required for a wind turbine.

Given this dilemma, the Windographer programme facilitates a virtual anemometer which is used to scale the wind speeds to reflect speeds at heights greater than that at which it was measured.. While this method of scaling is not an exact science, the extrapolation used is based on wind shear characteristics.

This approach however will suffice as the focus of this research is more concerned with the wind patterns rather than the precise wind measurement.

Wind shear refers to the change in wind speed with height above ground; wind speed tends to increase as the height above ground increases. The graphical representation of wind speed versus height above ground referred to as the wind profile is developed using the above mentioned method and is based on either the Log or Power law methodology.

Both methods utilize wind speed measurements made at a minimum of two heights in calculating the surface roughness and power law exponent for the Log and Power laws respectively.

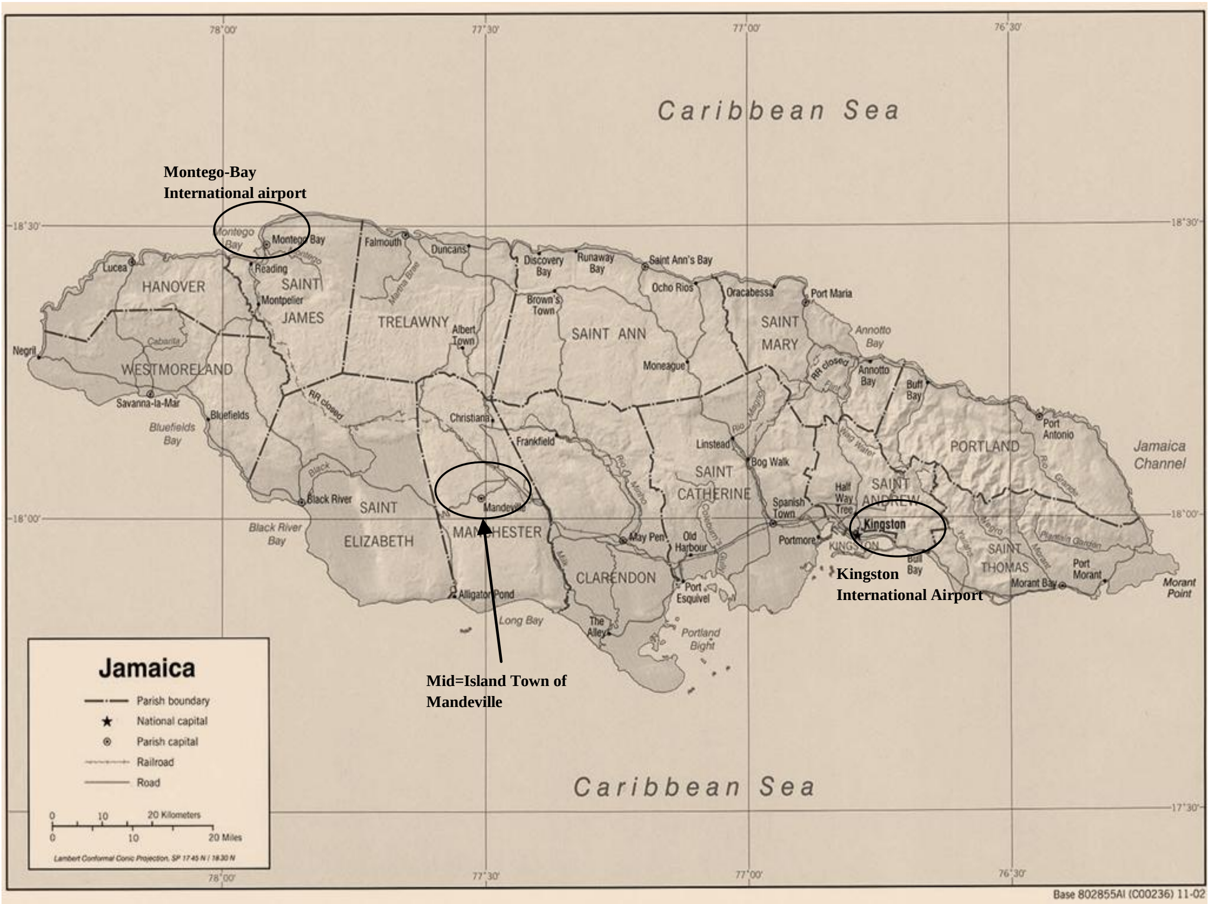

Figure 5.1: Areas on the Island for Which Wind Data was Available

However given the fact that such information is unavailable default values for these two measurements were used in scaling wind speed values up to 80 m.

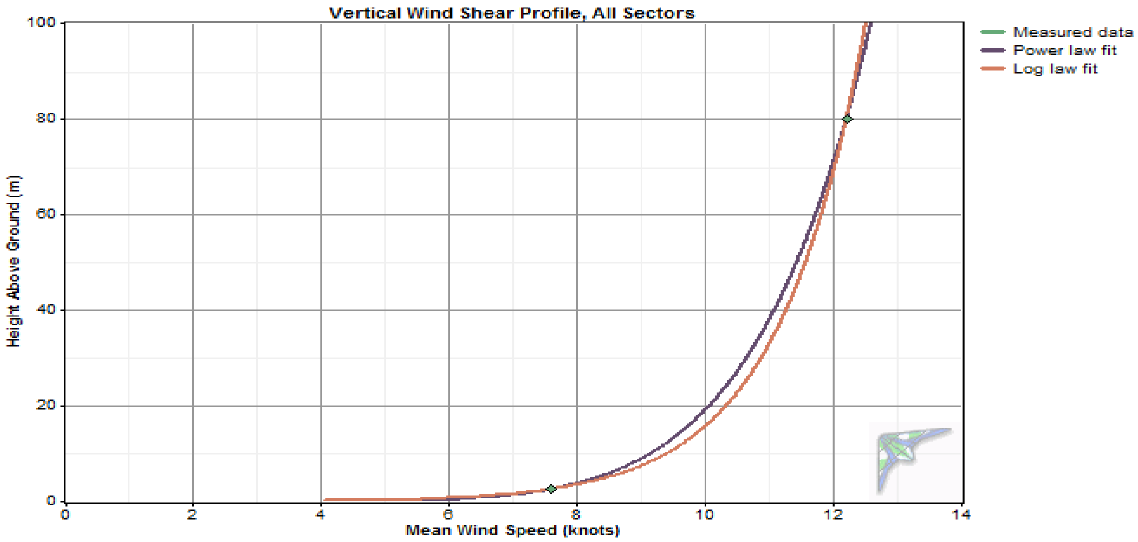

Figure 5.2: Log and Power Law Profiles for Norman Manley International Airport in 2004

Wind speed, based on the Log law varies in accordance with the mathematical expression:

$$\boldsymbol{V(x)} = \begin{cases} \dfrac{\boldsymbol{V^*}}{\boldsymbol{k}}\, \boldsymbol{ln}\left(\dfrac{\boldsymbol{x}}{\boldsymbol{x_0}}\right) & \boldsymbol{if\ x > x_0} \\ \boldsymbol{0\ \ otherwise} & \end{cases}$$

Equation 5.1

Where

V (x) is the wind speed (m/s) at some height above ground 'x' meters

V^* is the friction velocity - the velocity measured (estimated) near the surface. It is dependent on atmospheric conditions such as air density.

k- is the von Karman's constant

x_0 is the surface roughness (m).

Hence for a given surface roughness, the wind speed at a specified height, given the speed at another height, can be determined by:

$$\frac{V(x_2)}{V(x_1)} = \frac{ln(x_2/x_0)}{ln(x_1/x_0)}$$

Equation 5.2

Successive points can therefore be developed to produce the profile shown above in Figure 5.2.

The Power law profile is based on the mathematical expression:

$$V(x) = \beta z^{\alpha}$$

Equation 5.3

Where
V(x) is the average wind speed (m/s) at some height aboveground ‘x’ (m)

‘β’ is some constant in (m/s)

‘α’ is the power law exponent[24]

Hence for a given value of ‘α’, the wind speed at a specified height, given the speed at another height, can be determined by:

$$\frac{V(x_2)}{V(x_1)} = \left(\frac{x_2}{x_1}\right)^{\alpha}$$

Equation 5.4

Similar to the Log law successive points can be developed to produce the power law profile. For this research the Power law was applied using an exponent value of 0.14. The determination of the power law exponent or coefficient is developed in Appendix D.

Daily Wind Profile

The average daily wind speed for any period was determined by calculating the average speed of the wind for a specified time point or slot. While this data cannot be used to predict future wind speeds or generator output, it helps to provide guidance as to the measure of the prevailing wind patterns.
Ernst 1999 in the “*Analysis of Wind Power Ancillary Services Characteristics with German 250-MW Wind Data*”, used correlation to establish the relationship between wind turbine output and their respective proximity. A similar approach is herein considered by determining the relationship between the average daily profiles taken at the independent

[24] The power law exponent (sometimes called the power law coefficient) is a number that characterizes the wind shear, which is the change in wind speed with height above ground

sites for the years available. The cross-correlation used to conduct the analysis is based on the mathematical expression:

$$r_{ab} = \frac{1}{n\sigma_a\sigma_b}\sum_{i=1}^{n}(a_i - \mu_a)(b_i - \mu_b)$$

Equation 5.5

Where

μ_a and μ_b are averages of the two series ‘a’ and ‘b’ being considered

‘**n**’ is the number of points in the time series and

‘σ_a’ and ‘σ_b’ are the standard deviations of the time series.

A value for ‘r’ close to or equalling ‘1’ indicates that the variation in the average wind speeds bears a strong correlation, while a negative value near to or equalling ‘1’, indicates that the variations are in opposition to each other. Values tending towards zero indicate that there is no relationship between the two sets of data.

The data for ALCAN 2000 to 2005, Montego Bay 2003 and 2004 as well Normal Manley 2003 and 2004 were compared. The matrix below shows the level of correlation among them.

From the table sixty four percent (64%) of the correlations were greater than 0.9; this increases to eighty six percent (86%) for correlation above 0.8. Using this data as an indicative tool, it shows that there is consistency in the daily wind pattern across the Island.

Additionally, using an average cut-in wind speed of 5 m/s, useful wind is produced between the hours of; 0900/1000 and 1700/1800 for inland wind and 0400/0500 and 1900/2000 for the coastal regions.

Table 5.1: Daily Average Wind Profile Correlation Table

	ALCAN 00	*ALCAN 01*	*ALCAN 03*	*ALCAN 04*	*ALCAN 05*	*Mobay 03*	*Mobay 04*	*Manley 03*	*Manley 04*
ALCAN 2000	1.00								
ALCAN 2001	1.00	1.00							
ALCAN 2003	0.93	0.93	1.00						
ALCAN 2004	0.93	0.93	1.00	1.00					
ALCAN 2005	0.86	0.87	0.99	0.99	1.00				
Mobay 2003	0.99	0.99	0.90	0.91	0.84	1.00			
Mobay 2004	0.97	0.97	0.84	0.84	0.75	0.99	1.00		
Manley 2003	0.97	0.96	0.86	0.86	0.79	0.98	0.98	1.00	
Manley 2004	0.90	0.89	0.72	0.72	0.63	0.93	0.97	0.96	1.00

Monthly Wind Profile

Having satisfied oneself that a daily pattern exists, it was important to look at a longer term analysis. The average daily wind profile for each month for the annual data was then considered. In considering the monthly profiles for each of the years, the correlation for the central region was consistently strong. Variations were however identified in the coastal data. While in many instances the correlation was between coastal and inland as well as coastal and coastal; there was relatively weak correlation between east and west coast data. In a small number of instances however, the correlation was negative indicating opposing variations.

Reviewing the actual data for the years where correlations were either low or negative showed that data for the particular month reflected at least one of the following:

1. Severely distorted data – flattened or skewed average measurements

2. No data
3. Excessively high or low average wind measurements – i.e. the wind being at an almost constantly high or low value.

For table 5.2 below, when the actual data for Norman Manley (East end of the Island) was considered, it showed that the wind speed was consistently above fifteen (15) knots as illustrated in Figure 5.3.

Table 5.2: Daily Average Wind Profile Correlation Table for the Month of June

	Alcan 2000	*Alcan 2001*	*Alcan 2003*	*Alcan 2004*	*Mobay 2003*	*Mobay 2004*	*Manley 2004*
Alcan 2000	1						
Alcan 2001	0.99	1.00					
Alcan 2003	0.99	0.99	1.00				
Alcan 2004	0.98	0.99	0.98	1.00			
Mobay 2003	0.95	0.96	0.96	0.94	1.00		
Mobay 2004	0.91	0.87	0.89	0.82	0.91	1.00	
Manley 2004	-0.13	-0.19	-0.13	-0.20	-0.16	0.06	1

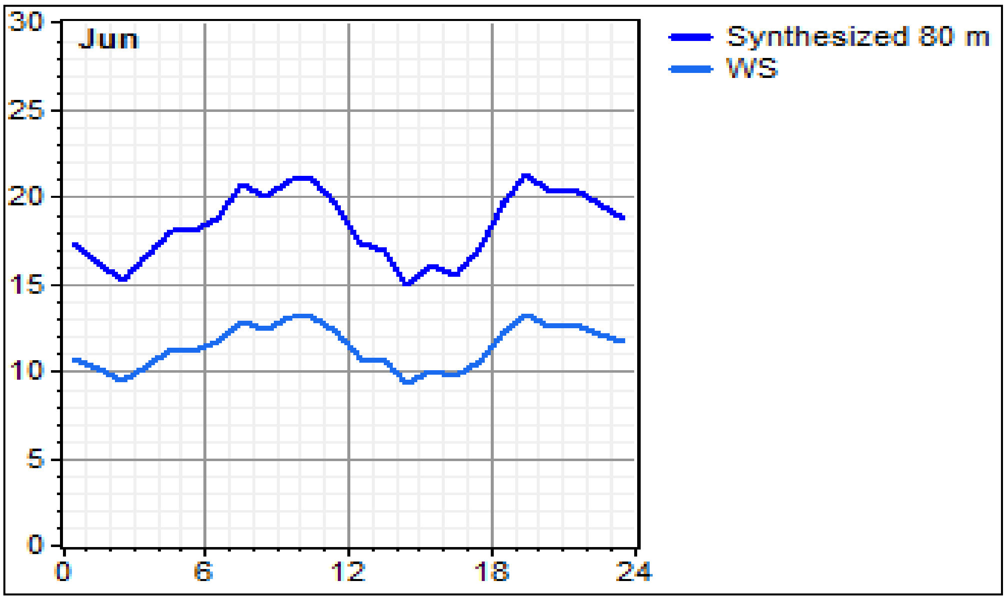

Figure 5.3: Daily Average Wind Profile month of June at the Norman Manley Airport

When compared to the data for ALCAN 2004, as shown below, the negative correlation could be correctly based on the fact that as the speeds for Norman Manley increased there was a decrease in wind speeds at ALCAN. Whilst no concrete reason have been established for the distortion in the June measurements at Norman Manley, there is a sufficiently high level correlation in the remaining data sets for acceptability.

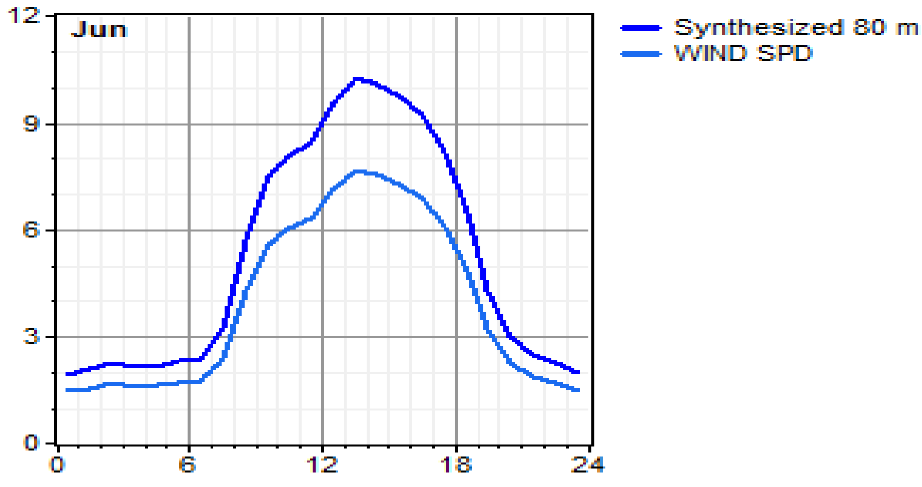

Figure 5.4: Daily Average Wind Profile month of June for ALCAN

Overall however, the correlation for the monthly data, after removing obvious distortions, ranked above 0.9. It is therefore acceptable to conclude that based on annual weather patterns, the average daily wind speed varies consistently from one month to the next over successive years.

The distortion in the original data set can, if not addressed, render the wind final wind data useless. There is therefore a built-in mechanism within the Windographer package that identifies and filters or gives the user the opportunity to filter the data before final processing. The programme identifies and fills gaps where appropriate, identifies and flags deviation from norms in the data. This helps to limit the number of errors that is passed through to the final data for use in general electrical output.

Seasonal Variation

Given the tropical location, Jamaica boasts primarily consistent temperatures year round. It is therefore difficult to accurately identify distinctive seasons for the Island. Notwithstanding this fact, there are clearly identifiable annual climatic patterns. The period November to March is clearly identified as the dry season, while May through to October represents the raining season, with peaks in both months.

In reviewing the available wind patterns and from other anecdotal evidence, it is clear that the period between February and August have the highest daily average wind speeds. September to November on the other hand have the lowest levels of wind. The remaining months[25] have wind speeds that fall in the middle and will therefore be joined with those in the low wind category. This results in two distinct "wind" seasons. This rather crude separation will allow analysis of the power input during high and low wind periods.

Annual Variation

Based on the available data and the correlation exercises conducted, it is evident that the annual wind pattern remains consistent. The correlation for the daily and monthly analysis remains above 90% for all the tests done on the five year data from the central region. It was

[25] It is commonly believed that December is one of the windiest months; however based on the available data this has been disproved. This belief about December is in part due to the fact that winds at this time of the year comes from the North American mainland and are therefore much cooler than wind at other times of the year.

however difficult to make a similar assessment with the coastal data owing to the distortions that were evident and the fact that only two years[26] of information was available.

Wind Measurement and Location

Jamaica's topography is characterized by a hilly interior stretching from the east to the west of the Island. The north and south coasts are however relatively flat. It was therefore important to determine the impact, if any of this kind of topography on prevailing wind speeds. Notwithstanding the challenges with the coastal data, it is clear that the magnitude of the wind speeds varied in accordance with the area from which the data was collected. The magnitudes on both coastal regions were consistently different from that in the inland area. To this extent, the modelling of wind farm output will reflect these differences.

[26] This data once updated can provide more precise analysis of the network operation.

5.2 Wind Generation

Wind Model

Having established a general characterisation of the prevailing wind pattern for the Island, it was now necessary to effectively produce a model that is a relatively accurate representation. The preferred approach is to use a probabilistic or stochastic method to first interpret the actual data then to generate the required model so as to replicate it as accurately as possible.

In its simplest terms a stochastic method/measure/process is a random function. The domain over which the function is defined can be time or space dependent; thereby defining a time series or a random field respectively. Wind, a key area of this research, is an example of a time series.

In probabilistic terms, a stochastic process consists of a random variable being defined on a probability space with values in a space of functions consisting of a set of functions.

5.2.1 Weibull Distribution

The Weibull distribution is a continuous probability distribution characterized by two principal parameters; namely the ‘scale’ and ‘shape’ parameters ‘c’ and ‘k’ respectively. These parameters help to define the variation of a quantity about a mean value.

The Weibull function of a distribution “U” is given by:

$$F(U) = e(^{-(U/c)^k})$$

Equation 5.6

For a quantity of long term average value $\overline{U}$, we have

$$\overline{U} = c\Gamma(1 + 1/k)$$

Equation 5.7

where Γ is the complete gamma function. This can be derived by consideration of the probability density function

$$f(U) = \frac{k}{c}\left(\frac{U}{c}\right)^{k-1} . e^{\left[-\left(\frac{U}{c}\right)\right]^k}$$

Equation 5.8

The shape factor helps to define the level of variance about the mean value, that is, the spread or breath of the data. For values that becomes consistently less than the average, 'k' has a value less than ' 1', for consistent values 'k' is equal to '1' while for values consistently larger and increasing 'k' is greater than '1'.

It has been found that the Weibull distribution gives a good representation of variation in wind speeds measured on an hourly basis. Given the need to determine the wind magnitude at 30 minutes intervals, where the wind 30 minutes earlier does not necessary dictate or impact current value; the Weibull methodology will be adopted.

Application of the Weibull Distribution

Given the ability to analyze data using a Weibull distribution, the object for this research is to first determine the shape and scale values of the wind data. Having determined these quantities it is then necessary to use them to generate random values of wind speed data.

The indicative information regarding the wind pattern, developed from the average daily, monthly and annual profiles, are also incorporated in the creation of the wind data.

Among these considerations are

1. The time of day – i.e. low wind period are separated from high wind periods
2. Seasonal data – data is segmented based on the definition outlined earlier
3. Data based on location.

The shape, 'k' and scale, 'c' values of the wind data can be determined using one of three methods. These methods include:

1. Maximum Likelihood Algorithm - MLA
2. Least Squared
3. Wind Atlas, Analysis and Application Programme – WAsP

Each of the three methods utilizes different algorithms in determining the parameters of the Weibull distribution. Given that the accuracy of the fit is dependent on the method used, it was instructive to use the method that provides the best fit for the probability density function of the wind speed data. While this may be determined by assessing the graphical fit, the goodness-of-fit, "R^2" parameter is used. "R^2" tending towards one (1) is an indication of a good fit.

This is illustrated below for the Weibull fit of 2004 data from the western end of the Island. From the given data, the least square method provides the best physical fit for the actual data; hence the parameters from this fit will be used in randomly generating the wind speeds for the selected period.

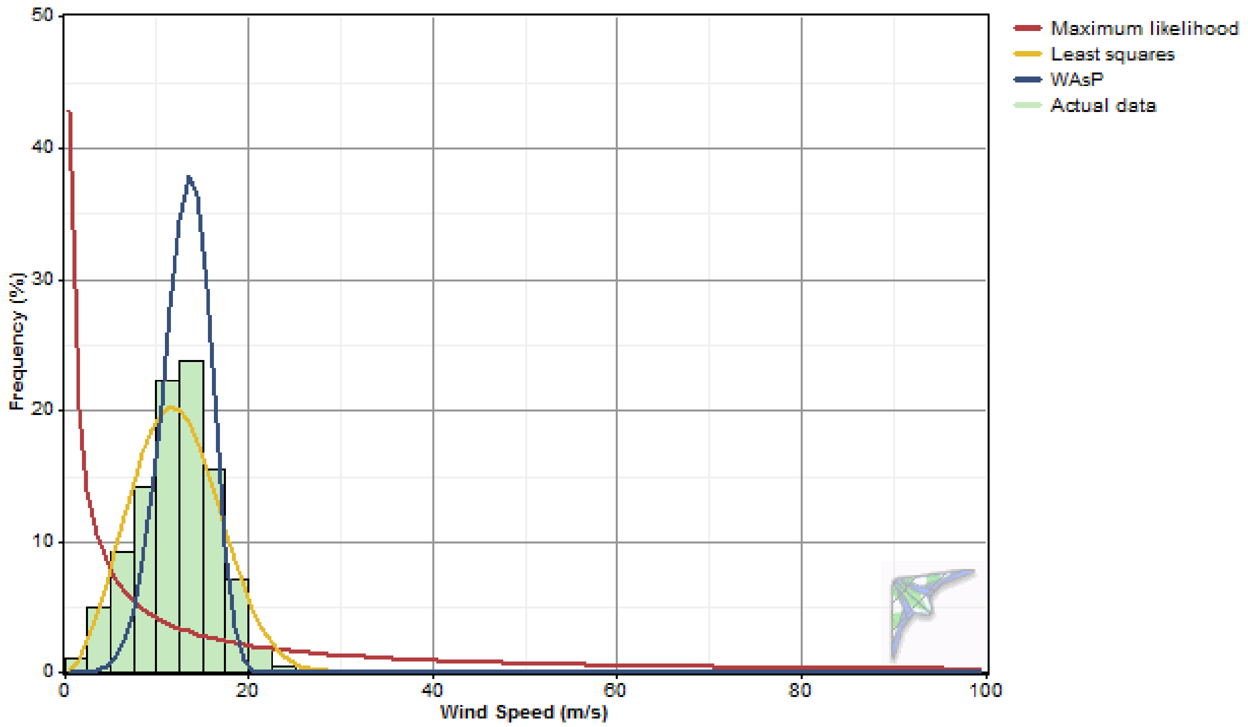

Figure 5.5: Weibull fit using Maximum Likelihood, Least Squares and WAsP Methods

The maximum likelihood algorithm and the least squares algorithm both attempt to fit a Weibull distribution directly to the measured wind speed distribution, and tend to produce similar results. The WAsP algorithm does not consider the shape of the actual wind speed distribution, but rather considers only its mean wind power density and its proportion of values above the mean; this approach results in parameters that are sometimes significantly different from that obtained using the other methods.

Given the objective of this research and notwithstanding the statement above regarding best fit algorithm, only the maximum likelihood and least square methods will be considered.

Maximum Likelihood Algorithm

The Maximum Likelihood Algorithm, MLA, employs the following equation to calculate, iteratively, the Weibull '*k*' parameter:

$$k = \left[\frac{\sum_{i=1}^{N} U_i^k \ln(U_i)}{\sum_i^N U_i^k} - \frac{\sum_i^N \ln(U_i)}{N}\right]^{-1}$$

Equation 5.9

Where U is the wind speed in time step "i", and N is the number of time steps.
Having determined the shape factor the scale factor is given by:

$$c = \left[\frac{\sum_{i=1}^{N} U_i^k}{N}\right]^{\frac{1}{k}}$$

Equation 5.10

Least Square Algorithm

Considering the cumulative distribution function of the Weibull distribution

$$F(U) = 1 - e^{-\left(\frac{U}{c}\right)^k}$$

Equation 5.11

Where "U" is the wind speed (in knots or m/s)

"c" – the scale factor in the same units as the speed and

'k" – a unit less shape factor

From equation 5.11 the following can be derived

$$-\ln[1 - F(U)] = \left(\frac{U}{c}\right)^k$$

$$\ln\left[\frac{1}{1-F(U)}\right] = \left(\frac{U}{c}\right)^{k}$$

taking the natural log of both sides

$$\ln\left\{\ln\left[\frac{1}{1-F(U)}\right]\right\} = \mathrm{k} * \ln\left(\frac{U}{c}\right)$$

$$ln\left\{\ln\left[\frac{1}{1-F(U)}\right]\right\} = k\ln U - k\ln c$$

Equation 5.12

Equation 5.12 is in the form $y = mx + c$; a plot of which produces a line of slope “k” and intercept “$-k\ln c$" .

Although both approaches are different the results for the most part have been proven to be similar in most instances. Where however there is wide or any major variation, the goodness fit is relied upon to determine the parameters used.

5.2.2 Wind Generation for the Island

To demonstrate the technique used, the wind information and subsequent randomly generated wind for wind information collected in the western end of the Island is shown below. Given that the wind data is collected at two-minute intervals, the number of data points exceeds the maximum number of rows that can be displayed by MATLAB. This further restricts the time slots that are considered. Using the indicative time slots listed earlier, the six time slots used are:

02:00-06:00	06:00-10:00	10:00-14:00	14:00-18:00	18:00-22:00	22:00-02:00

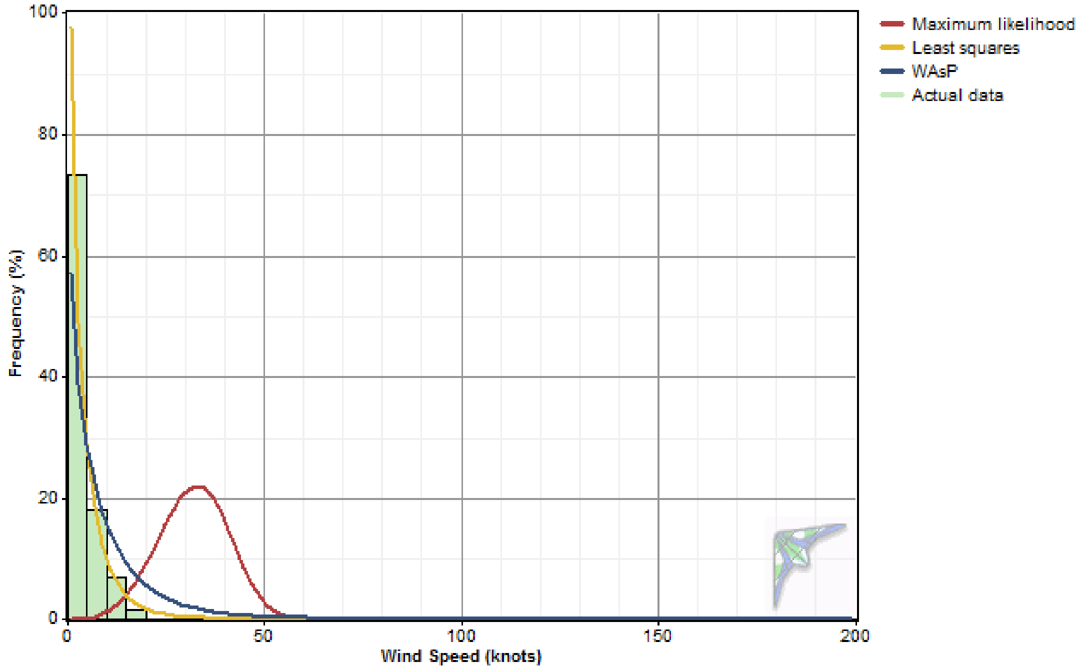

Figure 5.6: Wind measured between 02:00 and 06:00

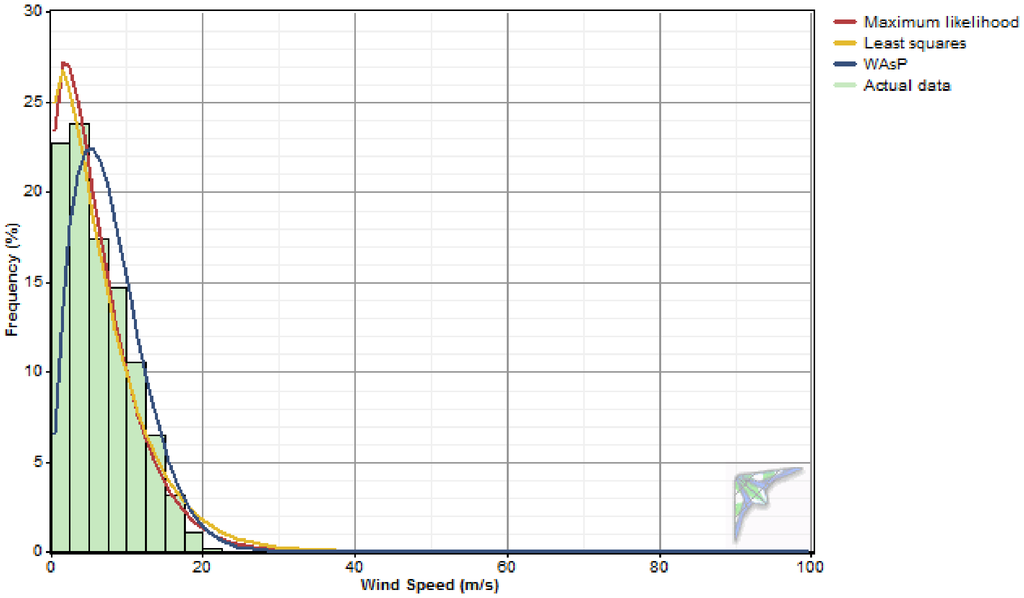

Figure 5.7: Wind measured between 06:00 and 10:00

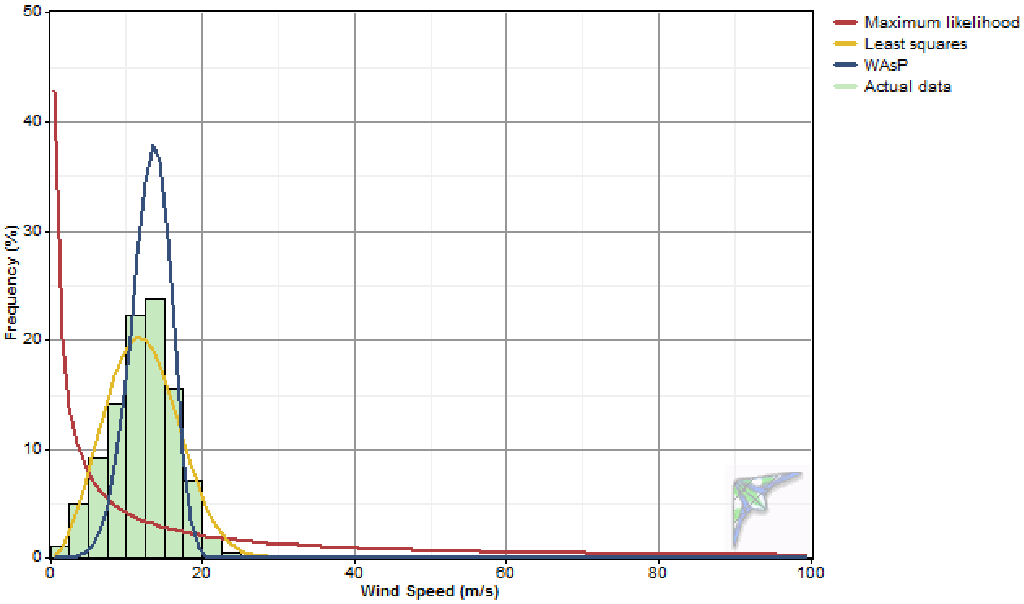

Figure 5.8: Wind measured between 10:00 and 14:00

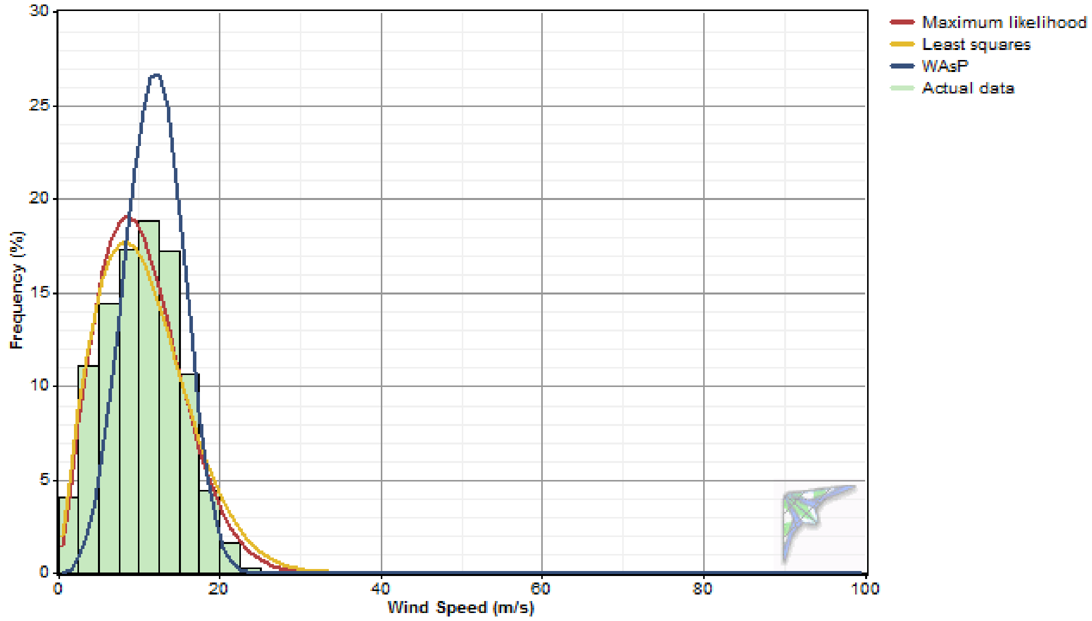

Figure 5.9: Wind Measured between 14:00 and 18:00

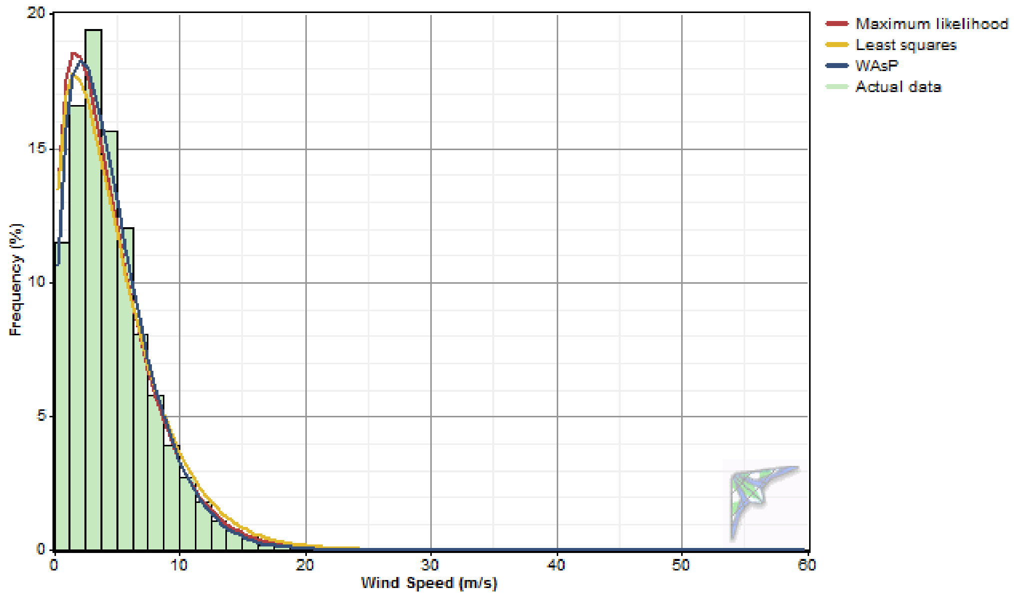

Figure 5.10: Wind measured between 18:00 and 22:00

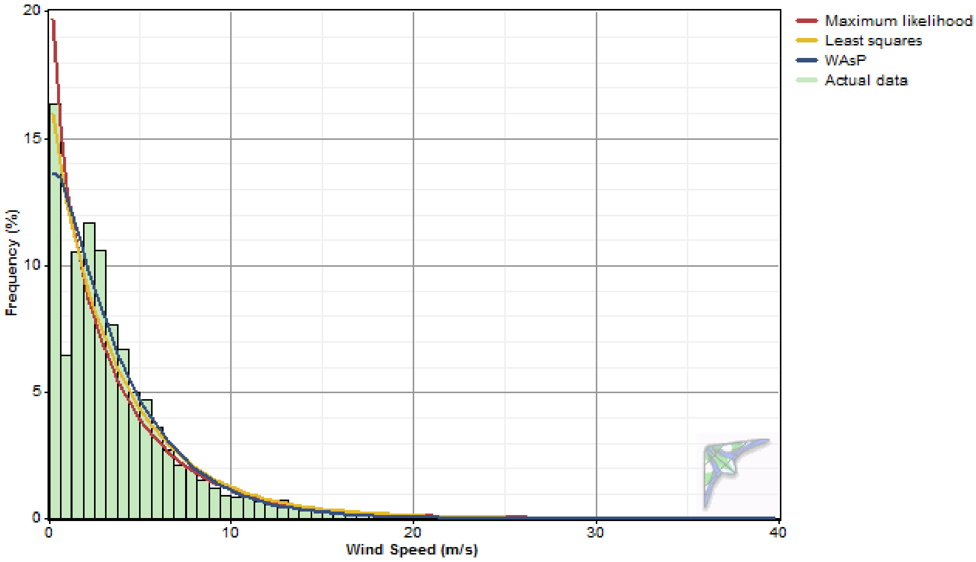

Figure 5.11: Wind measured between 22:00 and 02:00

The corresponding data tables are shown below:

Table 5.3: Weibull's Coefficients for Montego Bay Wind Regime 2004

Montego Bay 2004	Weibull	Weibull	Mean	Propor-tion	Power	R
06:00 to 10:00	k	c		Above	Density	Squared
Algorithm		(m/s)	(m/s)	Mean	(W/m^2)	
Maximum likelihood	1.241	6.788	6.333	0.4	582.2	0.95311
Least squares	1.169	7.147	6.77	0.391	799.9	0.94228
WAsP	1.699	8.69	7.754	0.439	654.7	0.94184
Actual data	(42,829 time steps)		6.378	0.439	654.7	
Montego Bay 2004	Weibull	Weibull	Mean	Propor-tion	Power	R
10:00 to 14:00	k	c		Above	Density	Squared
Algorithm		(m/s)	(m/s)	Mean	(W/m^2)	
Maximum likelihood	0.454	11.586	28.137	0.224	2,191,226.80	0.01644
Least squares	2.802	13.695	12.195	0.486	1,623.60	0.96746
WAsP	5.766	14.184	13.129	0.527	1,550.30	0.88871
Actual data	(42,946 time steps)		12.099	0.527	1,550.20	

Montego Bay 2004	Weibull	Weibull	Mean	Proportion	Power	R
14:00 to18:00	k	c		Above	Density	Squared
Algorithm		(m/s)	(m/s)	Mean	(W/m^2)	
Maximum likelihood	2.101	11.63	10.3	0.461	1,218.80	0.97
Least squares	1.961	11.935	10.581	0.454	1,413.60	0.96332
WAsP	3.68	13.154	11.868	0.504	1,304.20	0.8722
Actual data	(43,066 time steps)		10.361	0.504	1,304.20	

Montego Bay 2004	Weibull	Weibull	Mean	Proportion	Power	R
18:00 to 22:00	k	c		Above	Density	Squared
Algorithm		(m/s)	(m/s)	Mean	(W/m^2)	
Maximum likelihood	1.314	4.934	4.547	0.407	193.9	0.89663
Least squares	1.283	5.184	4.801	0.404	238.4	0.89214
WAsP	1.417	5.036	4.581	0.417	174.8	0.93982
Actual data	(42,751 time steps)		4.581	0.417	174.8	

Montego Bay 2004	Weibull	Weibull	Mean	Proportion	Power	R
22:00 to 02:00	k	c		Above	Density	Squared
Algorithm		(m/s)	(m/s)	Mean	(W/m^2)	
Maximum likelihood	0.899	3.536	3.723	0.351	252.4	0.55714
Least squares	0.975	3.889	3.932	0.364	238.3	0.66701
WAsP	1.077	3.779	3.673	0.379	152.7	0.75524
Actual data	(42,699 time steps)		3.682	0.379	152.7	

Montego Bay 2004	Weibull	Weibull	Mean	Proportion	Power	R
02:00 to 06:00	k	c		Above	Density	Squared
Algorithm		(knots)	(knots)	Mean	(W/m^2)	
Maximum likelihood	4.094	35.399	32.129	0.51	3,385.60	0.00633
Least squares	0.814	3.836	4.291	0.334	70.9	0.99853
WAsP	0.869	8.7	9.341	0.345	599	0.93447
Actual data	(42,766 time steps)		3.987	0.345	599	

Using the shape and scale factors derived, the random generation of wind speeds is made using the "**wblrnd**[27]" function in MATLAB for each time slot. The information is then fed back into the time series data and a reassessment conducted. The original Weibull parameters and those determined from the randomly generated wind speed data are shown below in table 5.4.

Table 5.4: Weibull Parameters Developed From Original and Generated Wind Speed Data

	Weibull parameters			
Time Slot	k - original	c - original	k - generated	c - generated
06:00 to 10:00	1.241	6.788	**1.2453**	**6.8181**
10:00 to 14:00	2.802	13.695	**2.7913**	**13.6658**
14:00 to18:00	2.101	11.63	**2.0966**	**11.658**
18:00 to 22:00	1.314	4.934	**1.3101**	**4.9192**
22:00 to 02:00	0.975	3.889	**0.9772**	**3.8739**
02:00 to 06:00	0.814	3.836	**0.805**	**3.8001**

As was expected the error in the values of 'k' and 'c' were very low. The highest percentage error values were 0.94% for 'c' values and 1.1% for 'k' values. Similarly, as was expected, the correlations between the original and generated values were approximately one (1).

[27] MATLAB function: A = **wblrnd** (c, k, N,1) where 'N' is the number of rows in the column matrix for the wind speeds. This value is determined based on the number of measure time point data from each time slot determined in the original data.

Table 5.5: Correlation Coefficients For Shape And Scale Factors For Original And Generated Wind Speeds

	k - original	*c - original*	*k - generated*	*c - generated*
k - original	1			
c - original	0.973876	1		
k - generated	0.999977	0.974255	1	
c - generated	0.972857	0.999978	0.973271	1

The recombined time series data does however reflect increased errors in the shape and scale values up to 13% and 5% respectively. However the correlation between the two sets of time series data was reduced to 0.95. In reviewing the monthly wind data for the period, it was seen that the level of correlation varied widely. The time series data are shown below:

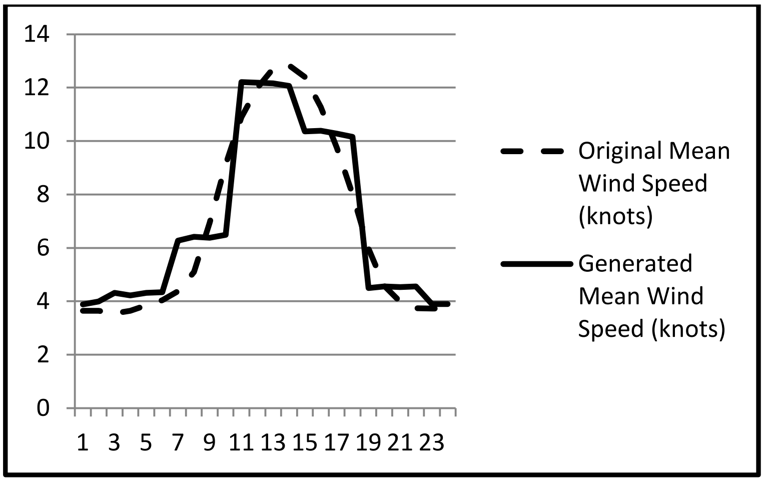

Figure 5.12: Time series original and randomly generated wind speed data

In order to determine any benefit of month by month (or seasonal) analysis to annual analysis; the data for June was assessed using the same methodology as applied to annual data. The results are shown below in Table 5.6:

Table 5.6: Percentage Error in the shape and Scale Factors and Corresponding Correlation for June

	k	c
Percentage error	9.6	3.8
Correlation	0.94	

Though improvement in the error measurements resulted, it is not considered sufficient in representing any meaningful improvement in the data to warrant month to month analysis. The proposed annual and seasonal analyses are therefore applied.

5.2.3 Other Wind Model Considerations

Turbulence

While not specifically derived from the available data it is assumed that the turbulence level at each site is within acceptable limits with a meaningful margin, to facilitate the wakes of the turbines.

Extreme Wind Speeds

The island is situated in an area where extreme winds from tropical storms frequently occur. No storm hitting the island has ever exceeded category five (5). Category 5 storms have maximum wind speeds of seventy five (75) m/s. For the purpose of this study it will be assumed that the turbines are capable of withstanding wind speeds of up to seventy (70) m/s. This speed represents IEC class 1 turbine [40].

Wind Farm Layout

The position of a turbine relative to another within a wind farm can affect the overall output of the facility. This is based on the fact that the speed of the wind falls after passing a turbine [22]. The phenomenon is known as 'wake'. The impact of wake is reduced by accurately locating turbines within the farm area. The effectiveness of the farm layout is dependent on the following:

1. Available land space
2. Terrain
3. Tower height
4. Number of machines

The optimization of these considerations is generally carried out using computer based programmes such as "Windfarmer". Once a proposed layout is obtained, it is further assessed with respect to the requisite infrastructure work.
For the purpose of this study it is assumed that all turbines are ideally placed and that the total output from the farm is the aggregate of the output of the turbines.

5.3 Wind Generator Model

Abraham Ellis et al posits [41] that equipment associated with the reactive power modelling of wind power plants, consisting of multiple generators and transformers, can be modelled using a single generator and transformer. Given that this study is concerned with the steady state analysis of the power system; this representation is also adopted. The four grid interface techniques being widely used:

1. Cage rotor induction generator[28]
2. Wound rotor induction generator with variable rotor resistance[29]
3. Doubly-fed induction generator with rotor side converter and
4. Full power generator[30]

can be represented using two techniques.

These techniques are based on the parameter that is being controlled or monitored at the output of the wind turbine. These parameter are, closed loop voltage, power factor and reactive power.

For types 1 & 2 listed above, the generator is represented as operating at a set power factor. Compensation for the required reactive power is then provided by switched capacitors at the generator bus. Further compensation can be provided at the substation bus for voltage regulation, if necessary.

Given the ability of the other connection types to adjust their power factor and also participate in voltage control, the use of reactive power compensation is optional. Noting however that the adjustment in power factor etc, is necessary through controller (physical input), the option is not always implemented. As such the use of Var compensation will be adopted. In maintaining power factors of 0.9 and 0.95 the reactive power is approximately 50% and 32% respectively, of the active power output.

[28] For fixed speed turbines
[29] OptiSlip – developed by Vestas
[30] Synchronous machines

Eduardo Muljadi et al [42] highlight the fact that notwithstanding the variance in the characteristics and output of individual turbines and their associated equipment, they can be represented by a single generator, generator transformer and associated line. The equivalent impedance of this single representation being the combination of those associated with that of each piece of equipment[31].

The general expression for the line/cable impedance, Z_s, connecting the series of turbines to the wind plant substation is given by:

$$Z_s = \frac{\sum_{m=1}^{n} P_{Z_m}^2 Z_m}{P_{Z_n}^2}$$

Equation 5.13

Where P_{Zn} is the power associated with the turbine closest to the substation. However, given that all the turbines are of the same rating and producing the same output the equivalent impedance is the sum of the line impedances associated with each turbine relative to an adjacent unit. This therefore corresponds to the impedance of the line between the substation and turbine furthest away. However given that the actual farm layout was not considered in this research, the overall loss resulting from the wind farm will be fixed based on typical cable impedance.

Similar to the line representation the general transformer impedance, Z_{TS}, representation is given by:

$$Z_{TS} = \frac{\sum_{m=1}^{n} P_m^2 Z_{Tm}}{\sum_{m=1}^{n} P_m^2}$$

Equation 5.14

Based on the assumptions that the transformers of all the turbines are similar, the equivalent impedance is equal to the impedance of a single unit. i.e. $Z_{TS} = Z_T$.

For the purpose of this research it is however assumed that all the turbines have the same operating characteristics, all have similar step up transformers and are linked to the transmission system via a single line. The model used will be based on the lines and cables

[31] Assuming that the current injection for all turbines is identical in magnitude and angle

used in the original network. The transformers parameters will also be adjusted as per their rating based on the system output. The generator will be a standard generating unit with power factor control of 0.9 and 0.95 [41]. The capacity of the generator will be equal to the installed capacity of the of the wind farm, limited by the land space available in an area and the size of the individual turbines. The actual daily output will be based on the daily wind profile earlier established.

Based on the aforementioned the power output of the Enercon E53 generator, for easterly winds, is shown in the figure below.

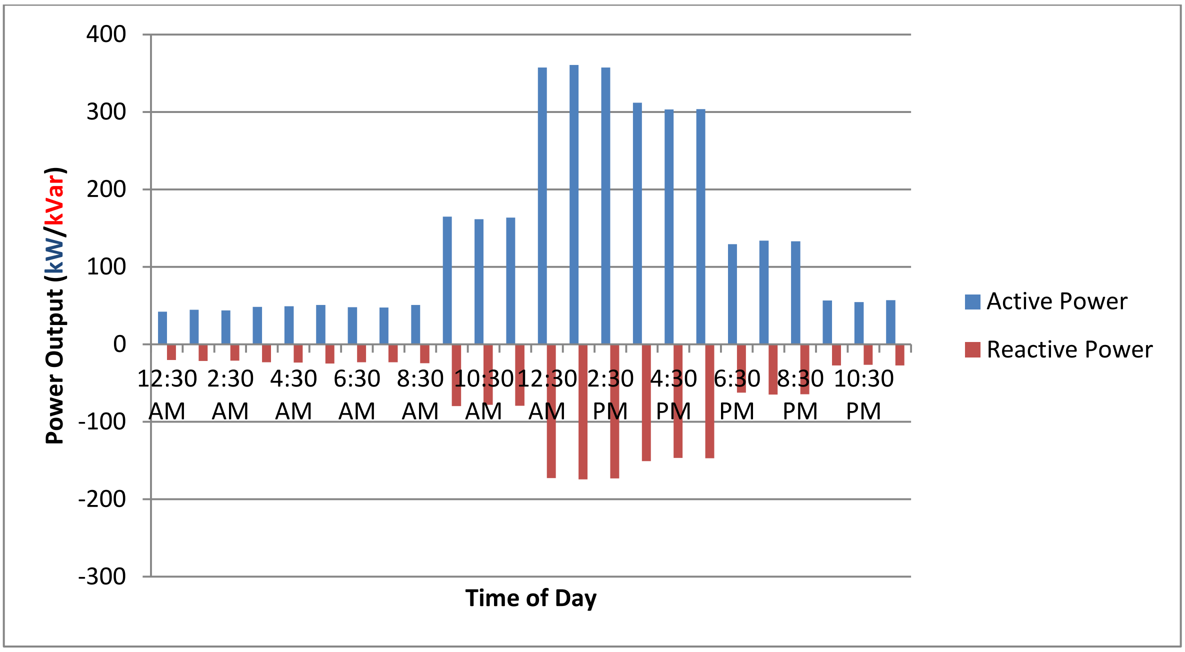

Figure 5.13: Active power output and corresponding reactive power requirement for an Enercon E53 wind turbine operating at a power factor of 0.9

The corresponding turbine model used has total capacity of 20 MW. The reactive power consumption is based on the capability curve shown below. The curve is derived from the actual output of Enercon E53 turbine. The reactive power requirement[32] displayed is based on the power factors of 0.9 and 0.95 as mentioned above.

[32] Based on the fact that it is absorbing reactive power from the capacitor bank and the network

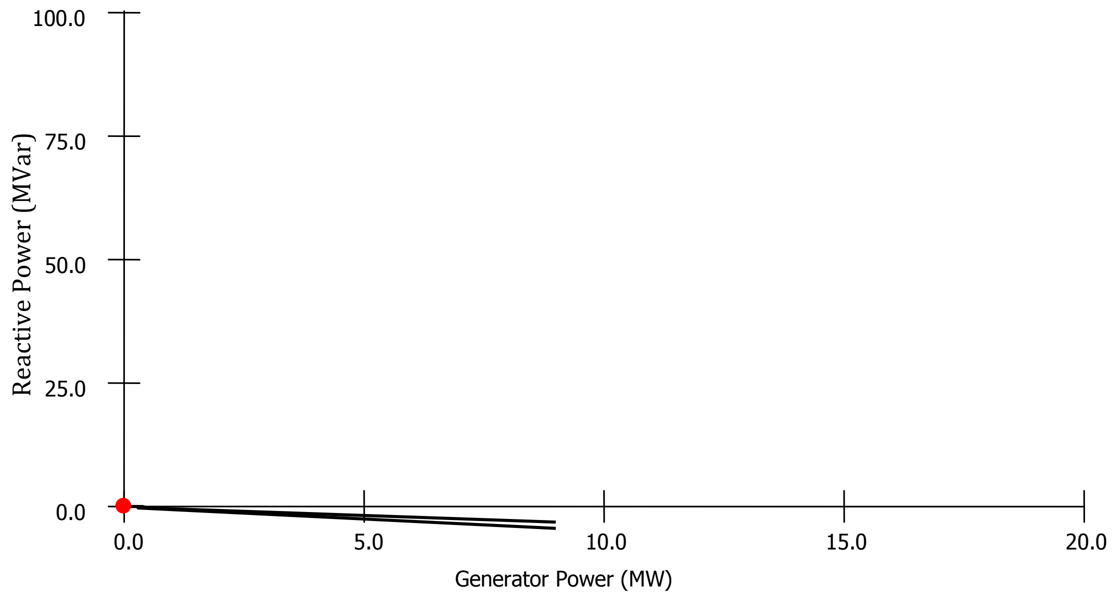

Figure 5.14: Reactive Power Capability Curve for Wind Farm

A transformer of rating in excess 10MVA and having a voltage on its high voltage side at or below 34.5 kV has a corresponding leakage reactance of between 0.055 and 0.075 "ONAN" and 0.09 and 0.128 "ONAF" [43]. The X/R ratio of a similar pad-mounted step-up transformer estimated of having a value of eight (8) [41][33].

Cost Model

The cost associated with the wind farm is based on the cost of equipment, land as well as operation and maintenance of the facility. The cost of generation is then determined by sum of the capital cost spread over a payback period of 20[34] years and the operation and maintenance.

With the benefit of the two projects mentioned in chapter two, the actual development cost of a wind project on the island were determined.

The installation of the JPSCo 3MW plant was reported as costing eight hundred million Jamaican dollars ($J800M). At the prevailing exchange rate this approximated to US$8.989M or US$2.99M/MW.

The Wigton project of 18MW is reported to cost fifty million US dollars (US$50M) or US$2.78/MW. Comparing these costs with that established by the National Renewable

[33] A leakage reactance of 6% is suggested, however with a power rating of up to 3MW.

[34] This is considered the average lifespan of a wind turbine

Energy Laboratory (NREL) estimates of US$2M/MW for large scale farms with higher cost for smaller facilities; an estimated cost of US$2.8/MW was considered acceptable.
Both facilities are being established on lands already used for wind power generation, hence the assumption being made is that the cost is for equipment, civil works and transportation etc. An additional amount for land is therefore included.

Based on data from NREL Power Technologies Data Book, the requirement for each 1MW wind turbine is approximately one quarter of an acre. This figure does not consider the actual terrain on which the turbine is located. Additionally, turbines are spaced between 5 and 10 times their diameter. Given that this however is not a major focus of this research and based on the assumptions regarding turbine output, the land usage per MW was estimated to be 1.0 acre inclusive of transformers, control rooms and any other attendant facilities. Consideration was also given to the fact that the wind farms were to be located in rural areas which would also affect land cost. Given however that even with the existence of the wind farm, land may still be used for some other productive activities, the lease of land is considered for this model. At current prices land lease on the Island is on average US$600 per acre.

According to the European Wind Energy Association, operation and maintenance cost are quite unpredictable, varying between twenty and thirty five percent of cost of energy produced. There was however no clear basis on which to model the O&M cost associated with wind generation. As such O&M cost for generation was equated to that of the most expensive fossil fuel unit used in the study.

Based on all these considerations the final cost per hour of the wind farms used was determined as follows.

For a 10 MW plant

Cost of equipment

Given the cost per MW established above, the total initial cost of the equipment and associated works is US$28M. Assuming an interest rate of 6%, the loan amortization over twenty years is equal to US$2.44M per annum. Given that this will be a fixed cost to the generator the amount incurred per hour is therefore US$278.67.

Cost of land is US$6000.00 p.a. or US$0.68 per hour. The total fixed cost is therefore US$279.35/h.

Operation and Maintenance costs as derived from JPSCo data are:

Variable cost – US$11/MWh

Fixed – US$ 2.17/MWh

Wind Farm Operation

Output

Wind farms used in the study are considered to be in blocks of 10MW. As such a 20MW farm is a combination of two blocks each consisting of the combined generator and its associated transformer and capacitor bank. Both are then connected to the single substation. Given the five areas being considered, reference is made to a 50MW or 100MW wind operation.

Peak Load Analysis

Based on current load data, the maximum load on the system occurs 71% of the time at approximately 7:00 pm and 14.5% at 6:30 pm and 8:00 pm respectively. The corresponding Wind plant output at 7:00 is therefore used for maximum load analysis

Timepoint Analysis

Timepoint analysis utilizes the actual twenty four hour operation of the wind generator based on the wind input and corresponding load.

5.4 Wind Generator Selection

5.4.1 Wind Turbine Technology

Wind turbine generator operations are based on fixed and variable speed concepts.

Fixed Speed Wind Turbines

Fixed speed operation means that the machine will operate at a fixed speed, regardless of the available wind speed. The speed is derived from the frequency of the supply grid, the gear ratio and other design features. Fixed speed machines utilises an induction generator directly coupled to the network. In addition to a soft starter the machine is equipped with a capacitor bank which reduces its reactive power compensation, see figure **4.30**.

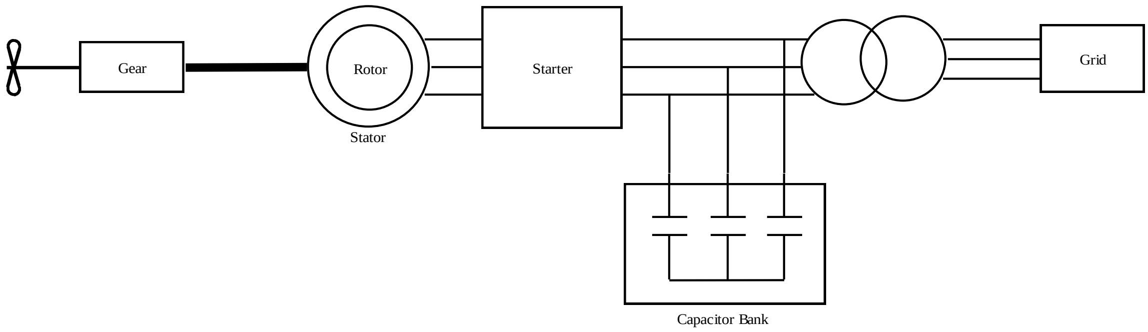

Figure 5.15: Fixed Speed Wind Turbine with Asynchronous Generator

[44]

Fixed speed machines are designed to operate at maximum efficiency at a specific magnitude of wind speed. However to maximize output power, the associated generators are equipped with two sets of windings, facilitating high output at high and low values of wind.

While the simplicity and robustness of such machines make them desirable, the inability to control their reactive power consumption and overall power quality makes their use, today, limited. Given that fluctuations in the wind speed is fed directly through to the network, the use of such machines on weak grids makes them undesirable, owing to the voltage fluctuations that would result.

Variable Speed Wind Turbines

As the name suggests, variable speed wind turbines are designed to achieve maximum efficiency over a wide range of wind speeds. This is achieved by varying the rotational speed of the turbine as per the wind speed, thereby maintaining a constant tip speed ratio. Variable speed machines use induction and synchronous generators, however unlike fixed speed units; they are coupled to the grid via power converters.

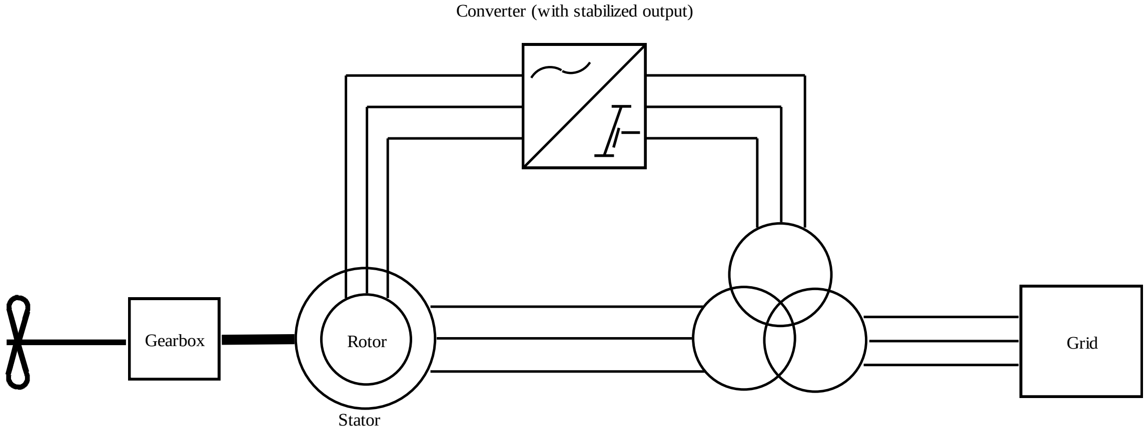

Figure 5.16: Variable Speed Wind Turbine with Double Fed Induction Generator

[44]

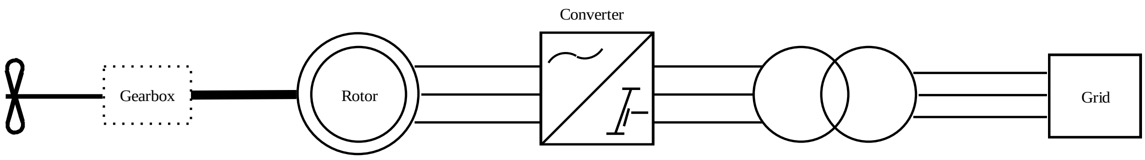

Figure 5.17: Variable Speed Wind Turbine with a Synchronous Generator

[44]

While the power converter allows for control of the generator speed, resulting in better power quality, it is also the main disadvantage associated with variable speed machines. The power converter results in additional power losses and in higher costs for variable speed systems. The introduction of variable speed machines also facilitates use of a wider range of generator/power electronic interface combinations.

Double Fed Induction Generator Systems

With the increase of economical and reliable power electronic circuitry, the Double Fed Induction Generator (DFIG) has become a viable option for wind power industry. The concept of double fed, relates to the fact that the voltage on the stator is derived from the grid while that on the rotor is induced by the power converter. The operation of DFIGs over a range of wind speeds is facilitated by the power converter; which injects a rotor current at variable frequency.

The total power is shared between the rotor and the stator P_r and P_s respectively, as per the machine slip (s).

$$P_r = s \times P_s$$

As such an inverter selected to allow a ± 'x' % control in rotor frequency will require the rotor converter to be rated at 'x' % of the stator power. The reactive power exchange between the system and the grid (controlled by the converter) can also be set within a predefined range, which restricts the voltage variation and reactive power losses. A typical power factor range is ± 0.9.

For the purpose of this study it is assumed that the necessary considerations are given to start-up and fault current contributions associated with induction machines. As such, consideration is given to the fault current magnitudes for the purpose of assessing the suitability of switchgear.

Synchronous Generator Systems

The synchronous generator unlike the induction machine does not require reactive magnetising current for its operation. The rotor winding is excited with direct current using slip rings and brushes or with a brushless exciter with a rotating rectifier. The stator winding which is directly coupled to the grid, results in the rotational speed of the machine being fixed as per the system frequency.

Unlike the DFIG, the converter is operated at full power and is therefore much more expensive. The converter serves as a buffer for power fluctuations that may result from wind gusts as well as transients from the network. It is also used to control the magnetisation to ensure the maintenance of synchronism with the grid frequency.

Synchronous machines are capable of generating and absorbing reactive power and therefore are ideally suited for the voltage control.
While from an engineering standpoint synchronous machines may be considered superior to induction generators, their cost makes their use limited in the wind industry.

5.4.2 System Interface

The benefits of wind energy is realised if the systems can be effectively and efficiently interfaced with the electricity network. Advances in power electronics has helped to facilitate these requirements. The technology has provided for devices that can reliably operate at higher voltages and currents and at gradually lower costs.
The three main pieces of hardware that need to be considered for effective operation of wind farms are:

1. Starters
2. Capacitors
3. Converters

Starters

Starters or more accurately soft starters are used in connecting induction generators in fixed speed systems, to the grid. Given the operating characteristic of these machines, soft starters are used to reduce the magnitude of the inrush current that would have otherwise resulted from suddenly connecting induction generators to the system. Inrush currents, which can be as high as eight times the rated current, can result in significant voltage fluctuations on the grid.
A typical soft starter consists of thyristors. The connection to the grid is a function of the firing angle of these thyristors. Once the inrush current has subsided, the thyristors are then bypassed to minimize power losses

Capacitors

Capacitors are used to provide VAR compensation for induction machines when used as fixed speed or limited variable speed induction generator systems. Generators can be designed to have a full load dynamic compensation. In such systems the total capacitance is adjusted based on the average reactive power demand of the generator over a predefined period of time.

Converters

Converters provide the mechanism for the interface between the direct and alternating current operational aspects of the generator and grid. The power flow at the grid side is controlled to keep the DC link voltage constant, while on the generator side the converter is set to provide the requisite magnetisation demand to produce the desired rotor speed. To achieve this, the converter provides for rectifier and inverter circuitry as well as energy storage capability.
The choice of the applied technology, is dependent on factors that include

a. cost
b. associated losses and
c. the effectiveness of applied control strategies

The power electronic interface in wind farms may be applied using different configurations, ranging from being fully distributed to being centralised. In the fully distributed system each turbine is fitted with its own electronic circuitry thereby facilitating each machine to fully exploit its prevailing wind conditions. At the other extreme the control is dispatched centrally which will result in each machine operating at the same speed, effectively nullifying the positive impact of variable speed systems.
For the purpose of this research, while the ideal configuration will be taken as distributed, simulation will reflect a centralised approach with parameters such as losses being treated as a component of the overall output of the farm.

5.4.3 Wind Turbine Option and Selection

The current Wigton[35] wind farm utilizes 900 kW Vestas[36] induction generators [4]. The proposed expansion of the facility will also utilize Vestas generators, however with an increased capacity of 2MW. Notwithstanding the original and continued use of Vestas

[35] Government of Jamaica owned wind farm through its subsidiary The Petroleum Corporation of Jamaica
[36] Originally NEG Micon

generators, it was important to determine what would be considered most appropriate for use on Jamaica, based on the wind regime developed for this study.
The first assessment was made based on the output of four (4) wind turbines. The turbines were assessed based on:

i. Peak output

ii. Hub height

iii. Response to low/medium and or high winds

iv. IEC Class[37]

While not assessed, the hub height and rotor blade lengths selected relied on the acceptance of similar specifications with respect to transportation, among other considerations, for the current Wigton expansion.

Based on the criteria listed, the following turbines were assessed:

i. Vestas[38]V80

ii. Acciona

iii. EnerconE70 and

iv. EnerconE53

[45]

The table and figure below shows the specification of each of the selected turbine technologies and their corresponding curves.
While the output power achieved by the different turbines vary at select wind speeds, as expected, it can be seen that the EnerconE53 and the Acciona AW70 have a higher percent output at the lower wind speeds. This suggests that at the lower speeds the capacity factor for these machines should be higher.

[37] Jamaica is prone to seasonal hurricanes. Although the Island has been hit by storms up to category 5 (i.e. over 155 mph or 70 mps), on average category 2 or 3 storms (i.e. 96 to 130 mph or 42 to 58 mps) are more likely. This corresponds to IEC class 1.
[38] Danish wind generator manufacturing company

Table 5.7: Table of Specification for the Selected Wind Generators

Generator	VestasV80	Acciona	EnerconE70	EnerconE53
Peak Output	2 MW	1.5 MW	2.3 MW	0.8 MW
Hub height	80m	80m	80m	60m
Response	Medium/High	Medium	High	Medium
IEC class	1A	1	1	1[39]

However as indicated above, it is necessary to accurately determine their actual outputs. Additional criteria that are considered include loss factors such as downtime, array, icing[40]/soiling and miscellaneous. While no accurate figures for these measures were available, estimates based on programme defaults were used, amounting to an aggregate of 13.1% in each instance.

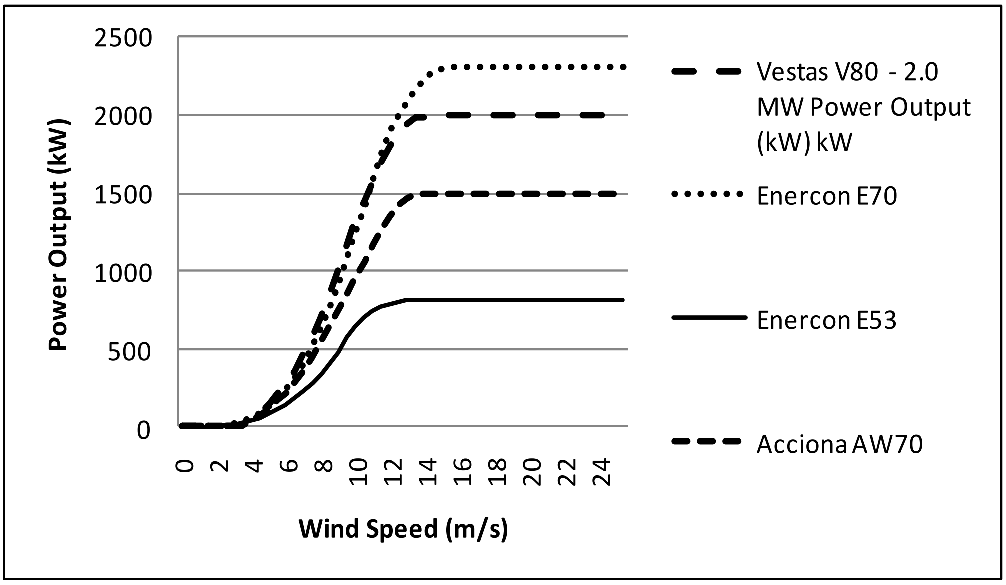

Figure 5.18: Comparison of Selected Wind Turbines

[45]

[39] Actually rated as IEC/NVN S up to extreme winds of 57 m/s

[40] While icing is used in the programme, the percentage for these conditions was reduced owing to the tropical location

5.4.4 Turbine Analysis

Figures 4.34 to 4.36 compares the four selected turbines based on their annual energy output, average annual capacity factors and the percentage of time each are at zero output. As expected, those units with the higher power capacity had the highest overall energy output for each regime.

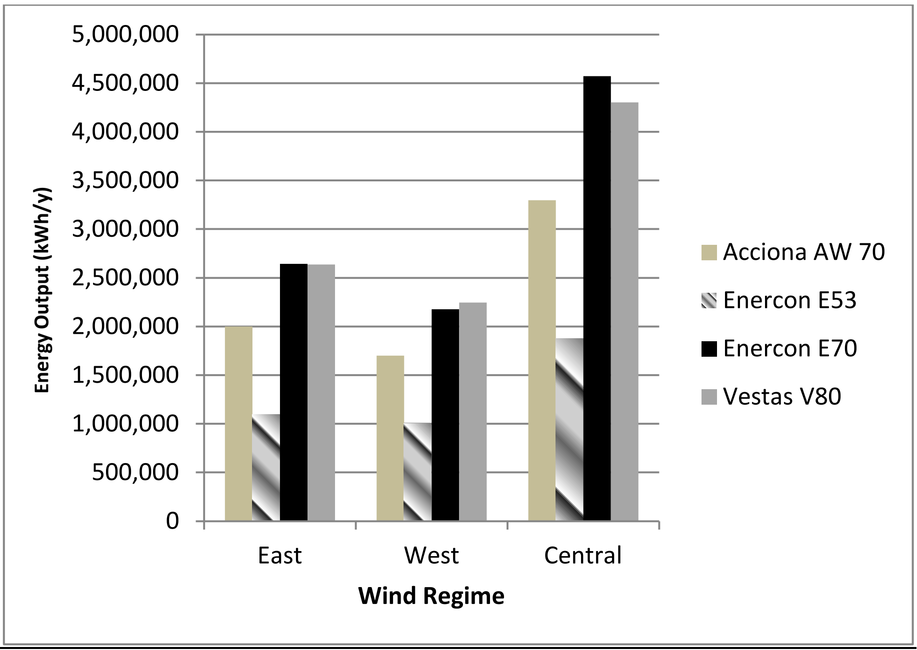

Figure 5.19: Energy Output of Selected Turbines for the Island's Three Wind Regimes

Although having the smallest aggregate output of the four turbines, the Enercon E53 had the best output relative to its capacity, in each of the three regions. The Enercon E70 however fared relatively poorly given its 2.3 megawatt capacity.

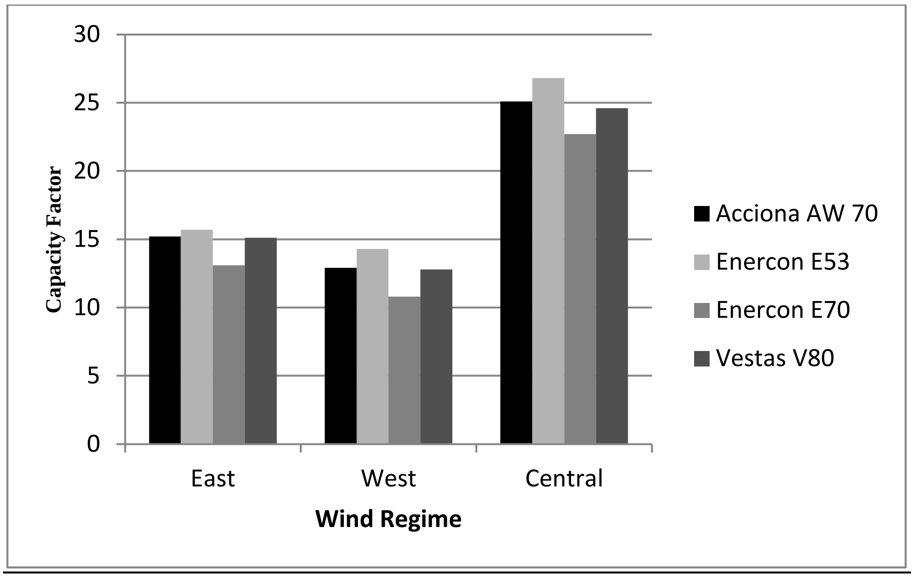

Figure 5.20: Capacity Factors of Selected turbines for the Island's Three Wind Regimes

The capacity factors of the units were all below the acceptable level of thirty percent (30%), reflecting the relatively low wind speeds. However in each area considered, the Enercon E53 outperformed the other three units. The unit correspondingly showed the least amount of time when output was zero.

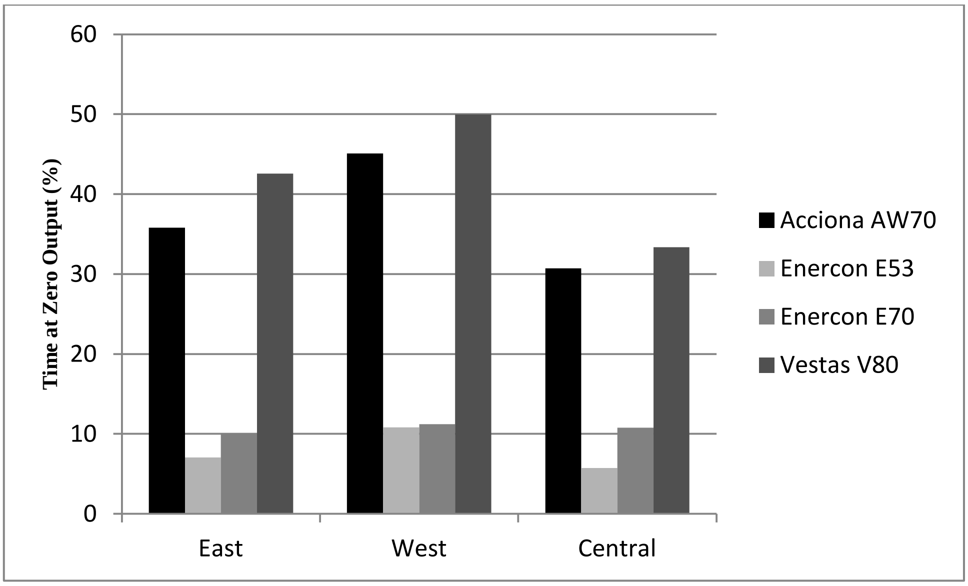

Figure 5.21: Time that Selected Wind Turbines are at Zero Output for the Island's Wind Regimes

Based on these observations, the generator output of the Enercon E53 will be used for this study. Given that the losses have already been considered, the total output from a potential farm will be determined by the product of the installed capacity and the percentage output from the selected generator. Higher megawatt output turbines will be considered where land space precludes such a small generator to be used.

Percent Output from Enercon E53

The daily wind profiles based on available annual data are shown below.

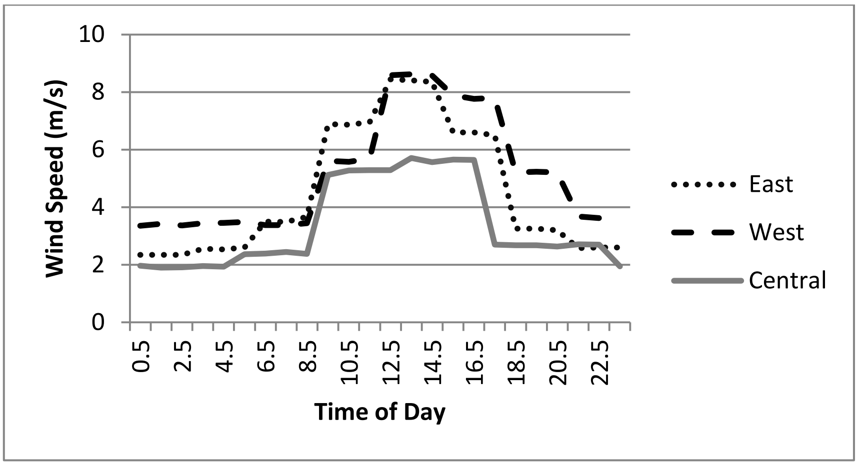

Figure 5.22: Generated Wind Regime for the Three Study Areas

The corresponding Enercon E53 output for each wind regime is shown in figure 4.38.

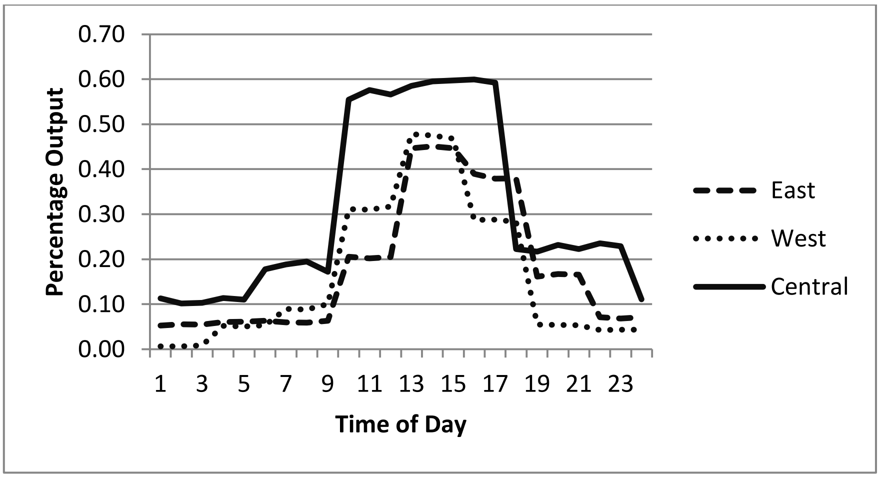

Figure 5.23: Daily Percentage Output of Enercon E53 Based on Annual Average

Further assessment of the turbine output was made based on months considered as high and low wind respectively, for each area. The peak and trough was made based on the month showing the maximum and minimum wind speed, which also coincided with the “windy” and “non-windy” seasons.

Figures 4.39 to 4.41 represent these comparisons.

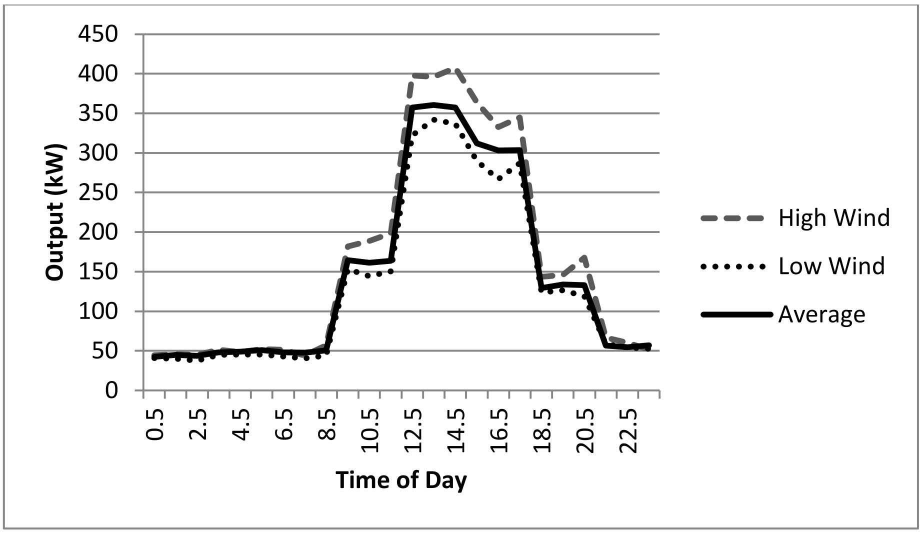

Figure 5.24: Output for an Eastern Connected Turbine

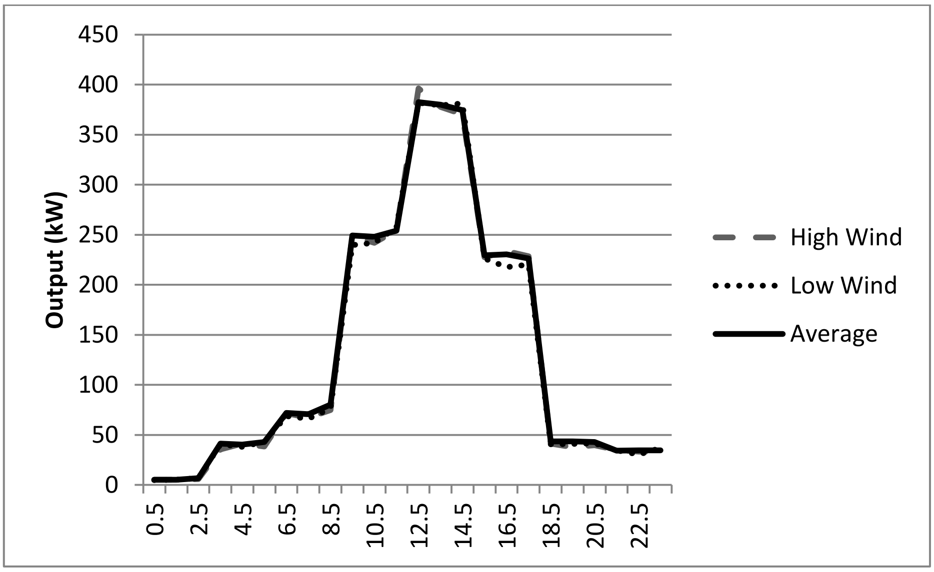

Figure 5.25: Output for a Western Connected Turbine

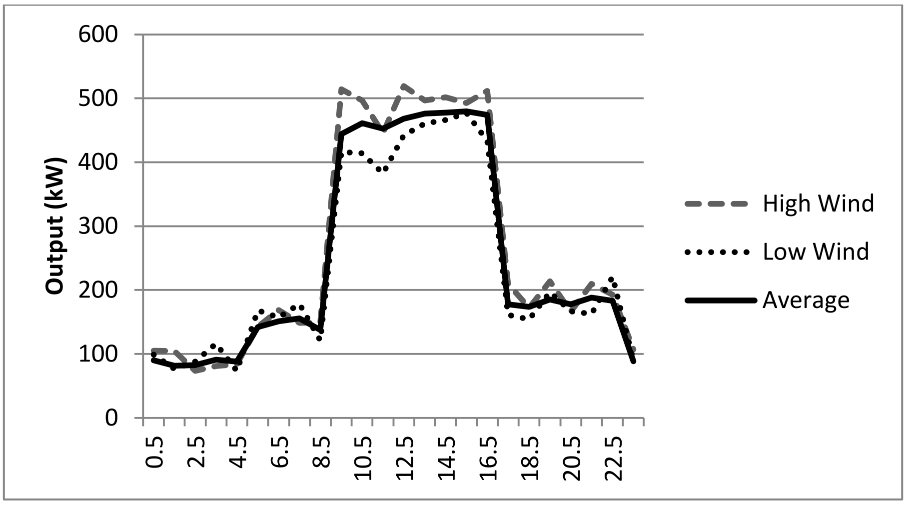

Figure 5.26: Output of Central Connected Turbine

Based on these comparisons, it can be seen that there are no significant differences among the three measures for each area. The relationship for each of the three areas is further supported by a correlation coefficient of 0.99.[41]

The wind regime for the three areas will therefore be based on the percentage output shown in figure 4.42.

The selected turbine uses a synchronous generator which produces an output voltage of 400V.

Vestas V80 Output Data

Given the current use of Vestas turbines on the Island, a study of their output is also considered for this study. Using similar considerations as the Enercon E53 turbine it was shown that the considerations for average, high and low wind were similar to that of the Enercon E53[42]; as such the average wind output was used.

The percentage output of this unit is shown below:

[41] See appendix E for further details.

[42] See appendix E

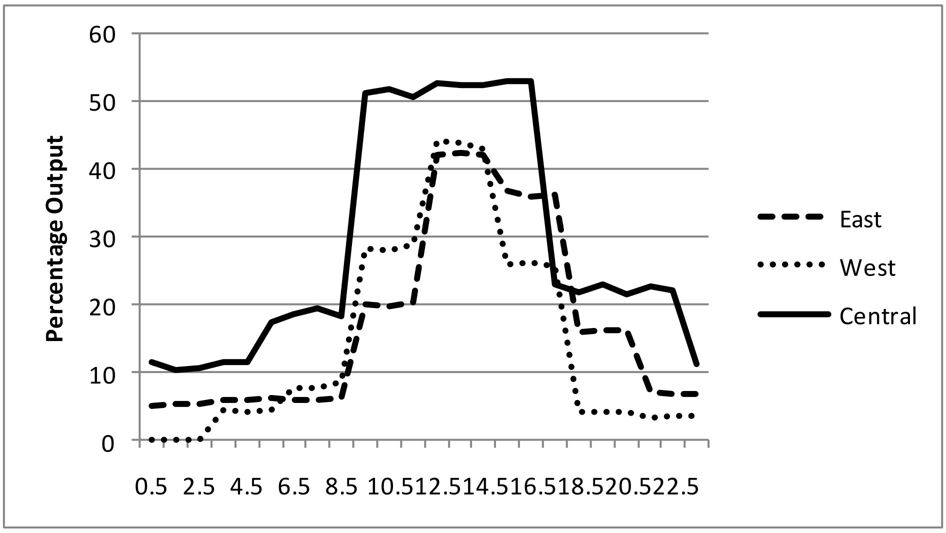

Figure 5.27: Daily Percentage Output of Vestas V80 Based on Annual Average

Unlike the Enercon 53, the Vestas V80 is an asynchronous machine, with an output voltage of 690V.

Plant Output for Peak Load Analyses

Based on current load data, the maximum load on the system occurs 71% of the time at approximately 7:00 pm and 14.5% at 6:30 pm and 8:00 pm respectively. The corresponding Wind plant output at 7:00 is therefore used for maximum load analysis.
The output of the Enercon E53 turbine is 185.24 kW at 1930 for a centrally located turbine. Given the aggregate plant output model (see above), the farm output for the 10MW model is;

P = (185.24*10000)/800 = 2.32MW

A 20 MW farm model utilizes two similar plant models operating in parallel into a common wind farm busbar.
The corresponding reactive power requirement is then established from the capability curve shown above.

Conclusion

We have been able to effectively generate random wind with a similar profile to the original data as well as format it to represent wind at a normal hub height. The proper review and modelling of the wind generator and farm has also been accomplished. We can now focus our attention on the estimation of green house gas production.

CHAPTER 6

Research Methodology – Pollution Measurements

Chapter 6 considers the measures used to determine pollution measurements in any network. It briefly considers some of the figures from the Jamaican perspective. The chapter concludes by considering an American standard for measuring and reporting and shows how this may be used in estimating such output within the Jamaican network.

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Introduction

The amount and type of oil consumed, design of combustion equipment, and application of emission control technology have a direct bearing on emissions from oil-fired combustion equipment. Further distinction is also made by virtue of the grade of oil used in the process.
Two broad categories of fuel oil are burned by combustion sources: distillate oils and residual oils. The two are further classified according to a number grading between 1 and 6 representing lighter to heavier fuels respectively. Electricity production from fossil fuels is done using numbers 2 and 6 (or bunker 'C') fuel oils in the electricity network. The heavier #6 fuel oil contains a higher concentration of pollutants than distillates. Among these pollutants are ash, nitrogen and sulphur.
Emissions from fuel oil combustion are further affected by the grade and composition of the fuel, the type and size of the boiler, the firing practices used, and the level of equipment maintenance. Baseline emissions are however derived from uncontrolled combustion of these fuels. Uncontrolled sources are those without add-on air pollution control equipment, low-NOx burners, or other modifications for emission control.
The chemical composition of fuel oil is dominated by carbon; it is therefore important to consider the production of carbon dioxide and monoxide during the combustion process. The majority of the carbon within fuels is converted to carbon dioxide during combustion. The small percentage that is converted to carbon monoxide is converted to carbon dioxide or ash after combustion. The rate of carbon monoxide emissions from combustion sources depends on the oxidation efficiency of the fuel. By carefully controlling the combustion process, carbon monoxide emissions can be minimized.
Small amounts of organic compounds are emitted from combustion. As with carbon monoxide emissions, the rate at which organic compounds are emitted depends on the combustion efficiency of the boiler. Therefore, any combustion modification which reduces the combustion efficiency will most likely increase the concentrations of organic compounds in the flue gases.
The methods used to reduce air pollution from fossil fuel combustion include:

- Fuel Substitution
- Combustion Modification
    - Particulate Matter Control
    - NOx Control

- Post Combustion Control-
  - Particulate Control
  - NOx Control
  - SO_2 Control

In summary the amount of pollutants emanating from the operation of the current utility company must be derived from full knowledge of its operations. Notwithstanding, one objective of this research is to determine, in some measure, the extent to which the use of renewable sources can mitigate against the production of pollutants. This method therefore falls under fuel substitution.

6.1 Emission Estimation

The Jamaica's National Energy Policy 2009-2030 [8], lists the barrels of oil equivalent for the energy production using wind and hydro electricity between the years 2004 to 2008. This is shown graphically below.

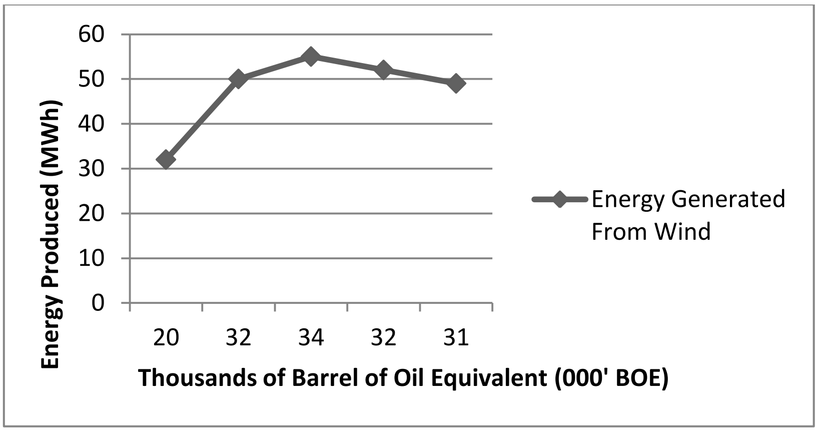

Figure 6.1: Barrel of Oil Equivalent for Wind Generated Electricity in Jamaica between 2004 and 2008

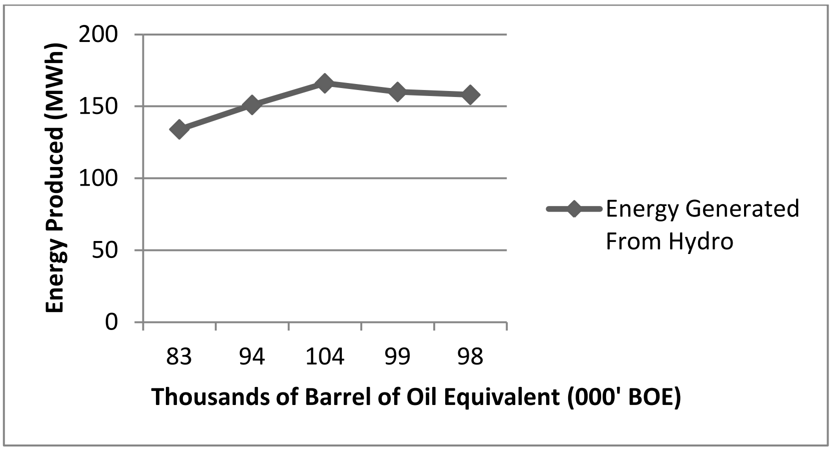

Figure 6.2: Barrel of Oil Equivalent for Hydro Generated Electricity in Jamaica between 2004 and 2008

The Emissions Inventory (2000 to 2005) of Jamaica categorizes GHG emission sources in accordance with the Intergovernmental Protocol on Climate Change, IPCC, into "*Energy"*, *"Industrial Processes and Product Use"*, *"Agriculture, Forestry and Other Land Use"*, *"Waste" and "Other".*

The energy category consists of mobile and stationary combustion, fugitive emissions and carbon dioxide transport and storage activities. The combustive activities are further subdivided into electricity generation, manufacturing and transportation.

The pollutants included in the inventory are:

i. Carbon dioxide
ii. Methane
iii. Sulphur dioxide
iv. Nitrous oxide
v. Nitrogen oxides
vi. Non-Methane volatile organic compounds (NMVOC)
vii. Carbon monoxide

The 2006-2020 energy policy based on the 1996 GHG emissions inventory estimated that twenty five percent of CO_2 emissions resulted from electricity generation. Based on the 2000 to 2005 figures, although the amount of CO_2 produced increased, as a result of increases in manufacturing and transportation, the average percentage produced by electricity ranged between 20 and 25%.

Other estimates for industries associated with electricity production are:

NO_x emissions – 18%

SO_x emissions - 29%

Notwithstanding the fact that other pollutants are produced their contribution even when grouped within the energy category is negligible relative to totals produced and will therefore be disregarded. As an example the vast majority of the methane and nitrous oxide output resulted from farming activities. Carbon monoxide production was also based primarily on transportation.

The table below shows the actual emission figures for the year 2000 (published in 2005) in Gg.

Table 6.1: Emissions for the Jamaica Energy Sector in 2000

Category	**CO_2**	**CH_4**	**N_2O**	**NO_x**	**CO**	**SO_2**
ENERGY	10,066	3.77	1.23	34	191	172

Notwithstanding the aforementioned, using this data to estimate the quantity of GHG emissions would be quite dubious at best.

6.2 Emissions Calculations

The Climate Registry, a non –governmental collaboration of North American states, provinces, territories and Native Sovereign Nations, has an agreed set of standards for the calculation, verification and reporting of GHG emissions. Within this framework, the registry provides calculation of emissions based on its General Reporting Protocol (GPR) as well as a protocol specifically for the Electric Power Sector (EPSP).

The EPSP provides options for the calculation of emissions for stationary combustion of fossil fuels based on the available data. The options available and the corresponding data requirements for the calculation of CO_2, CH_4 and N_2O, are set in tables 4.20 & 4.21.

Table 6.2: Direct Calculation of CO_2 Emissions from Stationary Combustion Facilities

Method	Type of Method	Data Requirements
EPS ST-01- CO2	Direct Monitoring	Continuous emissions monitoring (CEMS)
EPS ST-02-CO2	Calculation Based on Fuel Use	Measured fuel consumption, measured carbon content of fuel (per unit mass or volume)
EPS ST-03-CO2	Calculation Based on Fuel Use	Measured fuel consumption, measured heat content of fuels and default emission factor
EPS ST-04-CO2	Calculation Based on Fuel Use	Measured fuel consumption, default heat content, default emission factor

Table 6.3: Direct Calculation of CH_4 and N_2O Emissions from Stationary Combustion Facilities

Method	Type of Method	Data Requirements
EPS ST-08-CH4 and N2O	Calculation Based on Fuel Use	Source test based emissions factors; Measured fuel consumption and measured or default heat content

Given that only the fuel consumption for the utility company can be estimated in place of the measured criteria set out in the data requirements; method EPS ST-04-CO2 will be used.

The CO_2 fuel emissions using this method is given by the equation

$$CO_2 = Fuel \times HHV_D \times EF_{CO_2} \times 0.001$$

Equation 6.1

Where

CO_2 – Carbon Dioxide emissions for a specific fuel in metric tons per annum

Fuel – volume of fuel combusted specified by fuel type volume per year

$\mathbf{HHV_D}$ – default high heat specified by fuel type, MBtu per unit of volume

$\mathbf{EF_{CO_2}}$ - default CO_2 emissions factor based on the type of fuel

0.001 – conversion factor

The default emission factor values for the fuels in use by the utility company are listed in the table below.

Table 6.4: Default Factors for CO_2 Emissions from Fossil Fuels

Fuel Type	Heat Content (Mbtu/Barrel)	Carbon Content (kg C/MBtu)	CO_2 Emission Factor (per unit Energy) (kg CO_2/MBtu)	CO_2 Emissions Factor (per unit volume) (kg CO_2/gallon)
Distillate Fuel Oil #s 1, 2 & 3	5.825	19.95	73.15	10.15
Residual Fuel Oil (#s 5 & 6)	6.287	21.49	78.8	11.8
Crude Oil	5.8	20.33	74.54	10.29

Calculation of Methane and Nitrous Oxide production is also determined using equation 4.1. The default emission factors values associated with CH_4 and N_2O for petroleum products used in Electricity production are 3 & 0.6 respectively [46].

Fuel Consumption Determination

As outlined in the cost analysis, the fossil fuel generators were modelled as operating with one of four fuel types and technology combinations. These are:

1. Heavy Fuel Oil – Steam
2. Automotive Diesel Oil – Combined Cycle
3. Automotive Diesel Oil – Medium Speed
4. Automotive Diesel Oil – Combustion Turbine

Given that the generators using similar technologies were operated with the same efficiency, the input/output curves are also the same. The heat energy with respect to generator output power is given by the following equations as referenced in chapter 4.

1. Heavy Fuel Oil Steam Generating Unit –

$$\boldsymbol{H\ (MBtu/h) = 1.023P^2 - 39.26P + 613.9}$$

2. Automotive Diesel Oil Combined Cycle (ADOCC)

$$\boldsymbol{H\ (MBtu/h) = -0.006829P^2 + 5.796P + 104.1}$$

3. Automotive Diesel Oil Combustion Turbine (ADOCT)

$$\boldsymbol{H\ (MBtu/h) = 0.09637P^2 + 3.325P + 63.98}$$

4. Automotive Diesel Oil, Medium Speed Diesel (ADOD)

$$\boldsymbol{H\ (MBtu/h) = 0.1159P^2 + 4.891P + 16.61}$$

The calorific value of each fuel type is used to convert the heat rate from MBtu/h to bbl/h by:

$$bbl/h = \left(\frac{MBtu}{h}\right) \times \left(\frac{bbl}{MBtu}\right)$$

From the generic input/output curve in fuel consumption in bbls/hr versus power in MW, the fuel used by each generator can be determined based on its output.

As an example, the Bogue Combined Cycle generator at an output of 42.5 MW would be produced by a heat input of 338.1 MBtu/h. With a calorific value for diesel of 6.287 MBtu/bbl, the volume of fuel consumed is 53.777 bbl/h.

The corresponding CO_2 emissions at this level of production from equation 4.1 would therefore be:

$$CO_2 \;= \{(53.777) \times (6.287) \;\times (78.8) \times 0.001\} = 26.6419\; Mt/h$$

The CH_4 and N_2O emissions are therefore 1.014285 Mt/h and 0.202857 Mt/h respectively.

Global Warming Potential (GWP), measures the warming effect of a gas in terms of the effect of the equivalent impact of CO_2. The IPCC in its third assessment report (2001) provided GWPs of 23 and 296 for CH_4 and N_2O respectively. This means that the CO_2 equivalents for the emissions of these GHGs are 23.33 Mt/h and 60.05 Mt/h for CH_4 and N_2O respectively.

The total GHG emission for the operation of this unit at the output stated is therefore given by:

$$CO_{equivalent} = 26.6419 + 23.33 + 60.05 = 110.022\; Mt/h$$

The total CO_2 emissions are therefore calculated based on the sum of the individual units over the period under consideration.

CHAPTER 7

System Capacity Results and Comparative Analysis

Chapter 7 looks at and explores voltage levels, generation cost, fault levels, system loading and losses, and contingencies in order to assess the effect of embedded generation on the existing network. The impact of increasing the annual load demand on the network based on national projections is also considered. A comparative analysis of the impact of embedded generation on the system with respect to increased loading is also included. The analysis is made based on the peak demand as well as the demand spread over 24 hrs.

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Introduction

In order to fully appreciate changes that may occur with the power network it is necessary to clearly establish what the prevailing conditions are. Using the framework for analysis outlined in chapter 4 the operational data for generation, voltage and loading is first determined for the system as loaded in 2008. Consideration is given to both the operation of the system at its peak load as well as its operation over a twenty four (24) hour period in thirty (30) minute intervals; this based on the load profile established in chapter 2.

The operation of the system is then further considered given increases in load demand based on the annual growth of 2.5% up to the year 2020. The results are then compared to establish the impact on the system resulting from the increased load demand.

7.1 Reference Case Results and Analysis

In establishing the bases on which the effectiveness of embedded generation will be assessed, the state of the network with respect to:

1. Voltage Levels
2. Generation Cost
3. Fault levels
4. System Loading/Losses and
5. Contingencies

as described in chapter four is are herein referenced.

The criteria are first established based on the peak system load and then on the timepoint[43] data. The reference peak load of six hundred and twenty mega watts (620 MW) is the total system load in 2008.

[43] Timepoint data are the twenty four (24) hour input/output information for 30 minute intervals.

7.1.1 Voltage Levels

The voltage level/quality was based primarily on the bus voltages being within the range established by the service provider. As indicated earlier the acceptable voltage tolerance is five percent (±5%) of the nominal value. Given the fact that the study is a steady state analysis of the network flicker and other frequency related conditions are not considered. Though not explicitly dealt with, other operational standard related to voltage such as CAIFI[44] and SAIFI[45], are assumed to be positively affected by the achievement of acceptable voltage limits.

Per unit bus voltages for the Forty Eight load buses in the network ranged from a low of 0.946 to a high of 1.0. At the generator buses however of the twenty eight generating units, four operated with bus voltages below 0.95 while two operated above 1.05, which is illustrated in Figure 7.1 below. The voltage variance was based on the fact that each unit operated based on their participation factor.

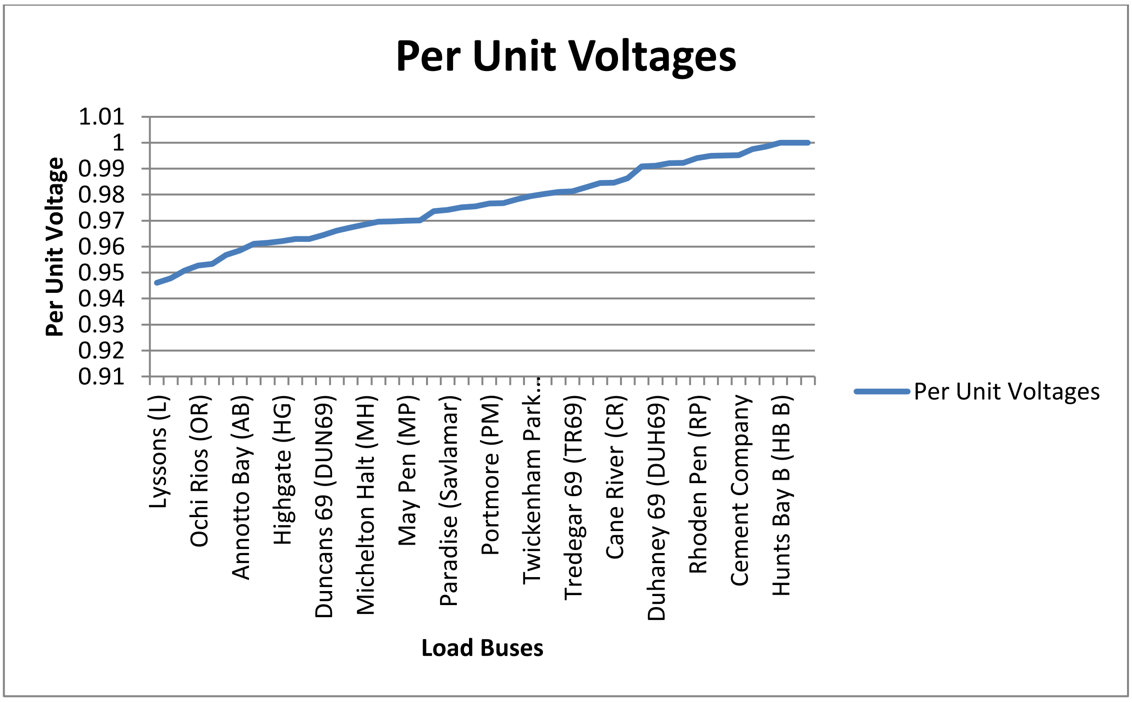

Figure 7.1: Per Unit Load Bus Voltages for the Current Network

[44] Customer Average Interruption Frequency Index
[45] System Average Interruption Frequency Index

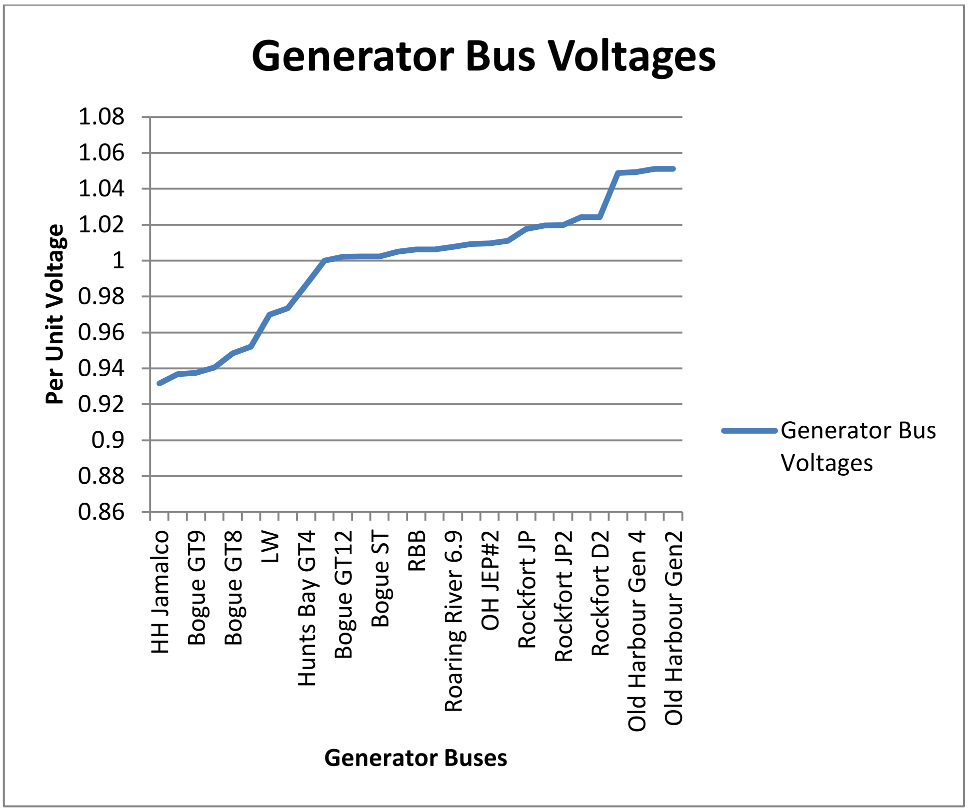

Figure 7.2: Generator Bus per Unit Voltage for the Current Network

Although some generator bus voltages were outside of the prescribed range; based on the participation factor mentioned in chapter four, the overall bus voltages at the controlled buses were equal to unity. As an example, the Bogue GT3, 7, 8, and 9 are all operating at voltages below 0.95 pu; the controlled bus, Bogue 69, is however operating at 1.00 pu. This is also true for the generators with bus voltages in excess of 1.05 pu.

7.1.2 Generation Cost

Generation costs associated with the study were based on generator operation data supplied in 2006. The fossil fuel prices used were however based on prices in 2007. The costs therefore produced should be regarded as indicative rather than actual present day costs. The costs established are based on individual generating units and the overall system. The output of each generator is based on optimal power flow (OPF) which is applied to all fossil fuel units. Fossil fuel units are all deemed to be operating on Automatic Generation Control and readily providing reactive power for voltage regulation.

Given that the actual dispatch algorithm for the company is unavailable, generator output is based on a participation factor. This factor is established as the percentage output of a generating unit, based on its rating and capacity in controlling the voltage at a particular busbar.

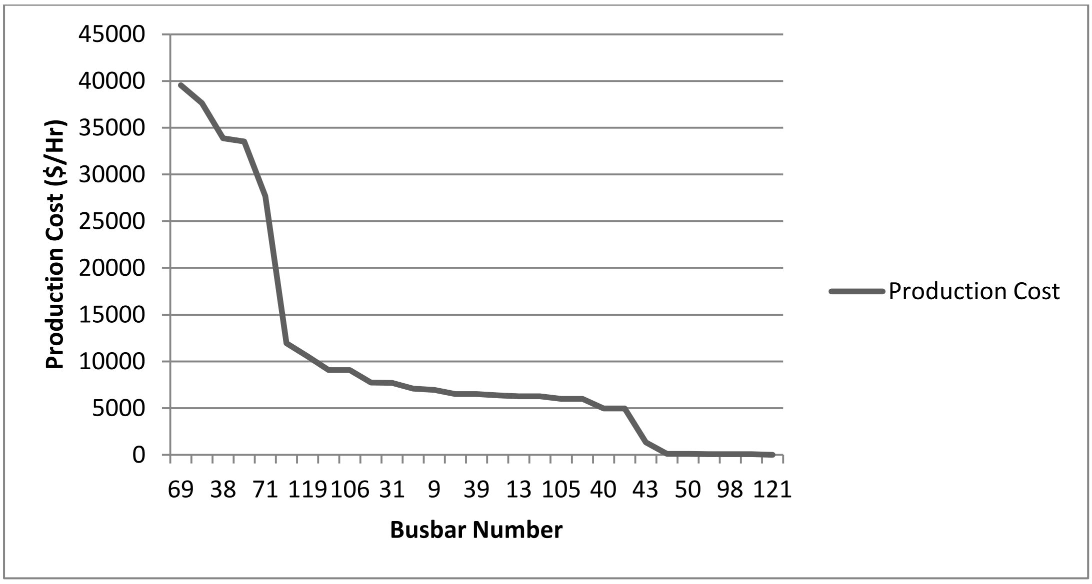

Figure 8.3: Generator Production Costs

The total costs for the production of Six Hundred and Thirty Four mega watts (634.25 MW), inclusive of transmission system losses, was $/hr 297 979.29.

Table 7.1: Generator Output Data for the Current Network

Bus Num	Generator Name	Output (MW)	Production Cost $/Hr	Incremental Fuel Cost
69	Old Harbour Gen 3	58.5	39543.79	418.17
72	Old Harbour Gen2	53.9	37617.49	418.17
38	**Hunts Bay B6**	**44.9**	**33853.74**	**418.17**
70	Old Harbour Gen 4	44.07	33537.99	418.17
40	Bogue GT13	39.5	4959.1	121.99
41	Bogue GT12	39.5	4959.1	121.99
43	Bogue ST	39.5	1329.72	32.71
118	OH JEP#1	34.16	11961.91	441.7
119	OH JEP#2	30.93	10536.69	441.7

Bus Num	Generator Name	Output (MW)	Production Cost $/Hr	Incremental Fuel Cost
71	Old Harbour Gen 1	30.15	27689.5	418.17
107	Rockfort JP2	27.39	9083.25	398.48
106	Rockfort JP	27.39	9083.25	398.48
105	Rockfort D2	18.37	5995.09	337.98
104	Rockfort D1	18.37	5995.09	337.98
11	Bogue GT9	16.61	7724.96	231.81
31	Hunts Bay GT10	16.47	7692.8	231.81
122	Bogue GT 11	13.7	7096.45	195.87
9	Bogue GT3	11.17	6939.92	253.25
45	Hunts Bay GT5	10.69	6507.62	195.85
39	Hunts Bay GT4	10.69	6507.62	195.85
12	Bogue GT6	9.99	6370.39	195.87
13	Bogue GT7	9.31	6262.15	159.93
10	Bogue GT8	9.31	6262.15	159.93
16	MG2	5.93	105.28	6
50	LW	4.5	96.7	6
127	Roaring River 6.9	4	93.7	6
98	UW2	3.39	90.04	6
19	RBB	2.35	83.8	6
121	HH Jamalco	0	0	0

The table above shows the output of each generator along with their corresponding production and incremental fuel costs.

7.1.3 Fault Levels

Fault levels provide the basis for the rating of the protective equipment to be used in the network. For this study the fault level at the load buses are referenced as it is assumed that the appropriately rated switch gear are used for generating units. The figure below shows these values:

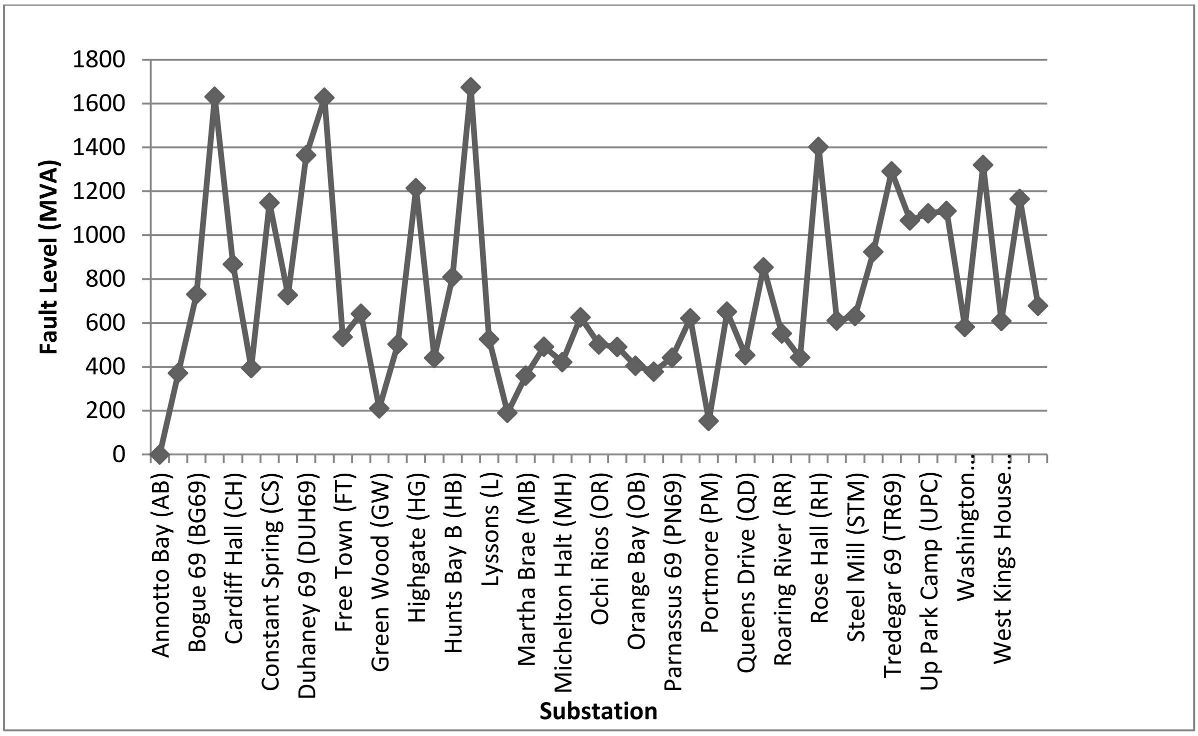

Figure7.4: Fault Level at Load Buses for the Current Network

7.1.4 System Loading/Losses

The system loading took into consideration the percent loading on the lines and transformers. The corresponding MW losses are also established. Transformer loading was placed in four categories: units loaded

1. up to Fifty percent of their MVA rating
2. between Fifty and Eighty percent of their MVA rating
3. between Eighty and One Hundred percent of their MVA rating
4. above their MVA rating

The transformer ratings shown in Figure7.5 indicate that Five percent (5%) of the units in the network are operating above their capacities. The two units are the Lower White River Hydro-electric and the Tredegar interbus. While such a condition would be considered unacceptable for normal operation, it is being overlooked in this study for the following reasons.

The Hydro units are all considered to be producing their maximum output at all times. They are also not identified as being AGC capable. At this maximum and based on the unit specifications, the transformer will operate at 102% of capacity.

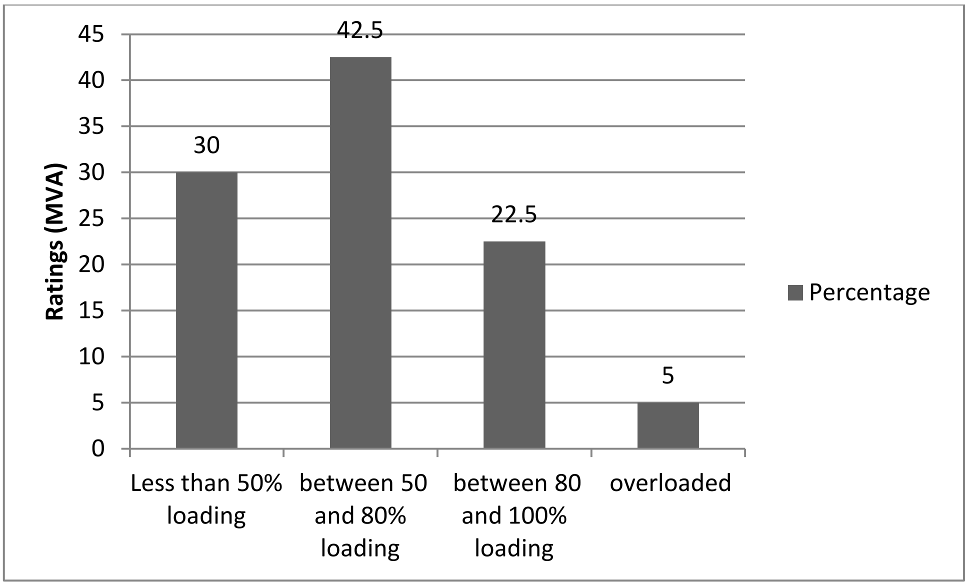

Figure7.5: Percentage Transformer Loading for the Current Network

The interbus 22 MVA transformer is set for equal load sharing with the larger 100 MVA unit. As such the approximately 23 MVA load on each results in it being loaded to 104% of its rating.

Four of the five[46] hydroelectric units make up the eleven transformers having loadings in excess of 80%. The other units in this category are units associated with the generating units producing near their peak output.

The remaining two categories are evenly spread across the other generating units and interbus transformers.

The transmission lines in the system had an average rating of Four Hundred and Ten MVA (410 MVA). Based on their ratings the loading on these lines ranged from a low of 0.8% to a high of 12.7%. The range is further highlighted in the figure below. Over 90% of the transmission lines in the system being loaded to below 10% of their capacity.

[46] *The other has a loading of over 70%*

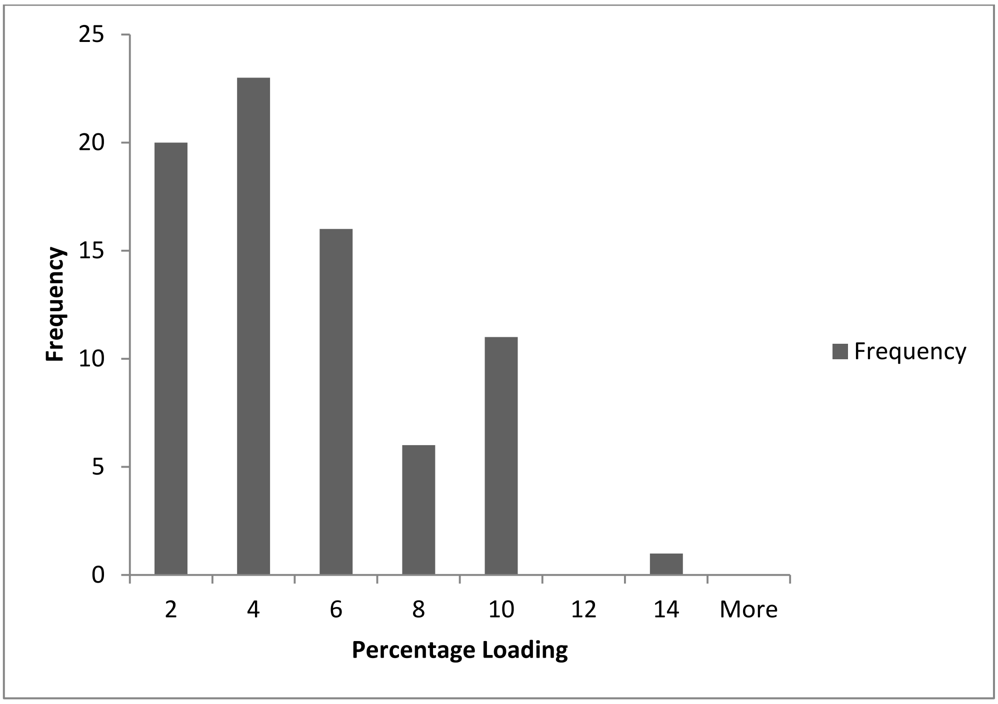

Figure 7.6: Percentage Loading of Transmission Lines for the Current Network

7.1.5 System Contingencies

The contingency studies conducted were based on the N-1 criterion. A total of 154 contingencies were conducted. These consisted of 29 generator; 42 transformer and 83 line contingencies. The system violations that resulted from generator contingencies are shown in table 5.2.

The vast majority of the violations listed, occurred in the Tredegar interbus transformer and the Lower White River generator transformer. As indicated in the system loading limits shown above, both transformers were overloaded under normal steady state operation. The problem was therefore exacerbated and or repeated for each contingency.

Table 7.2: Line/Transformer Violations for Generator Contingencies for the Current Network

To Bus Name	From BusName:1	Contingency Violation	Line Percent Loading (Max)
Hunts Bay A (HB A)	Hunts Bay B6	6	128.27
Old Harbour 138 (OH138)	Old Harbour 69 (OH69)	1	114.82
Tredegar 138 (TR138)	Tredegar 69 (TR69)	21	114.63
Old Harbour 138 (OH138)	Old Harbour Gen 4	1	104.94
Lower White River (LWR)	LW	28	102.44
Roaring River (RR)	Roaring River 6.9	1	100

The Hunts Bay B6 violations occurred primarily as a result of the loss of major generating units from the Old Harbour power station. Given that the unit is connected to the system slack bus, the increased loading resulted from the generator seeking to compensate for the significant short fall[47]. Correspondingly the violation for the Old Harbour units resulted from the loss of the Hunts Bay B6 contingency study.

There was however no bus voltage violations as a result of the generator contingencies.
The network violations that occurred as a result of line or transformer contingencies are shown in Table 7.3.

Similar to the violations observed for the generator contingencies, the overwhelming majority of violations occurred on the Tredegar and Lower White River transformers. It was also noted that all the overloading violations took place in transformers.
While the significant number occurred on the units named above, the other violations resulted from the rerouting of power as a result of the isolation of lines on the northern coast of the island.

[47] *It is a common in the operation of the Jamaican power network to have load shedding as a result of loss of any of these units, whether for maintenance or from fault conditions*

Table 7.3: Transformer Violations for Transformer Contingencies for the Current Network

To Bus	From Bus	Line/Xfmr	CTG Violation	Line Percent Loading
Tredegar 138 (TR138)	Tredegar 69 (TR69)	Yes	107	137.58
Bellevue 138 (BEL138)	Bellevue 69 (BEL69)	Yes	11	133.92
Hunts Bay A (HB A)	Hunts Bay B6	Yes	6	128.27
Duncans 138 (DUN138)	Duncans 69 (DUN69)	Yes	1	123.4
Old Harbour 138 (OH138)	Old Harbour 69 (OH69)	Yes	3	114.82
Old Harbour 138 (OH138)	Old Harbour Gen 4	Yes	1	104.9
Lower White River (LWR)	LW	Yes	124	102.44
Roaring River (RR)	Roaring River 6.9	Yes	4	100

This meant that the feed from the southern side of the island was required to supply loads that had greater supply from the generating units on the north-eastern end.

The voltage violations shown in Table 7.4 were all low voltage violations. These resulted primarily as a result of lack of Var support.

Table 7.4: Busbar Violations for Transformer Contingencies

Bus Name	Nominal Voltage	CTG Violation	Maximum Voltage Contingency	Minimum Voltage Contingency
MonyMusk (MM)	69	1		0.9
May Pen (MP)	69	1		0.9
Roaring River 6.9	6.9	1		0.9
Orange Bay (OB)	69	1		0.89
Lyssons (L)	69	2		0.88
West Indies Pulp and Paper (WIP)	69	1		0.88
Good Year (GY)	69	2		0.88
Free Town (FT)	69	1		0.87
Cardiff Hall (CH)	69	3		0.87
HH Jamalco	13.8	2		0.87
Upper White River (UWR)	69	1		0.86
LW	6.9	2		0.86
Lower White River (LWR)	69	2		0.85
Roaring River (RR)	69	3		0.83
Ochi Rios (OR)	69	3		0.82

7.1.6 Daily Load Analysis

The total system generation and corresponding transmission losses are shown in figures 5.7 and 5.8 below. Based on this level of production and the assumption made regarding annual/diurnal load fluctuations, the total daily and annual energy consumptions are:

Table 7.5: Generation Output and Transmission System Losses for the Current Network

	Energy Produced (MWh)	**Corresponding Transmission Losses (MWh)**
Daily	**13,390.95**	**277.01**
Annually	**4,887,696.75**	**101,108.65**

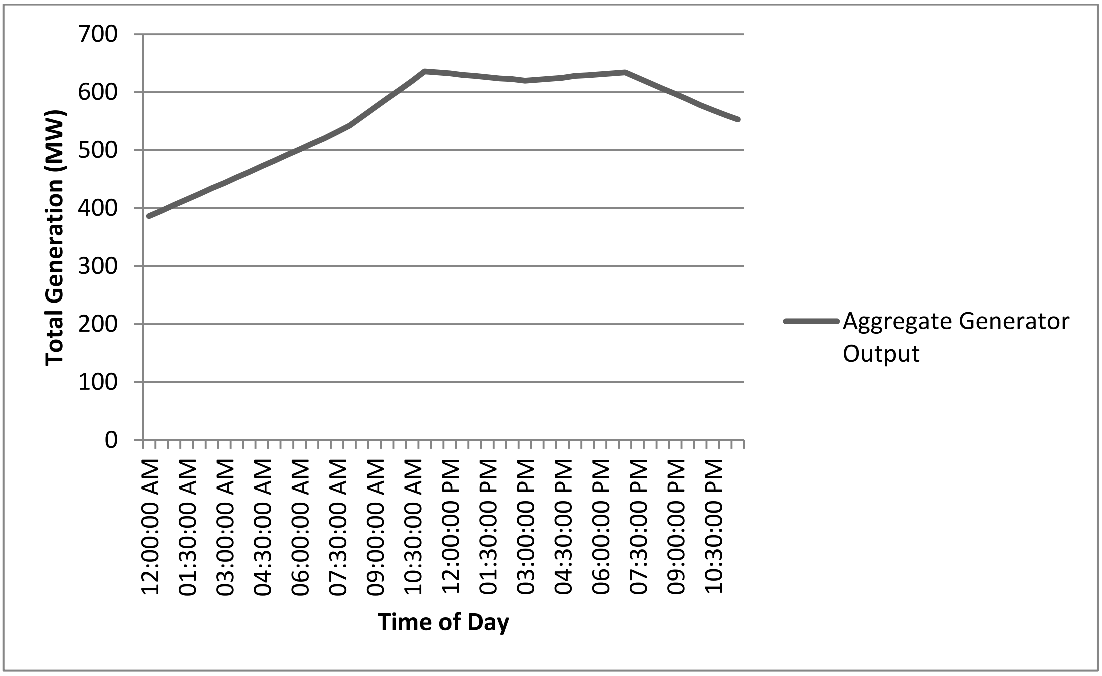

Figure 7.7: Aggregate Generation Output for the Current Network

The losses shown, has values greater than the losses calculated at maximum load. This resulted from the fact that the loads varied based on the profile associated with particular busbars.

The spinning reserves[48] in the system are also highlighted in Figure7.9.

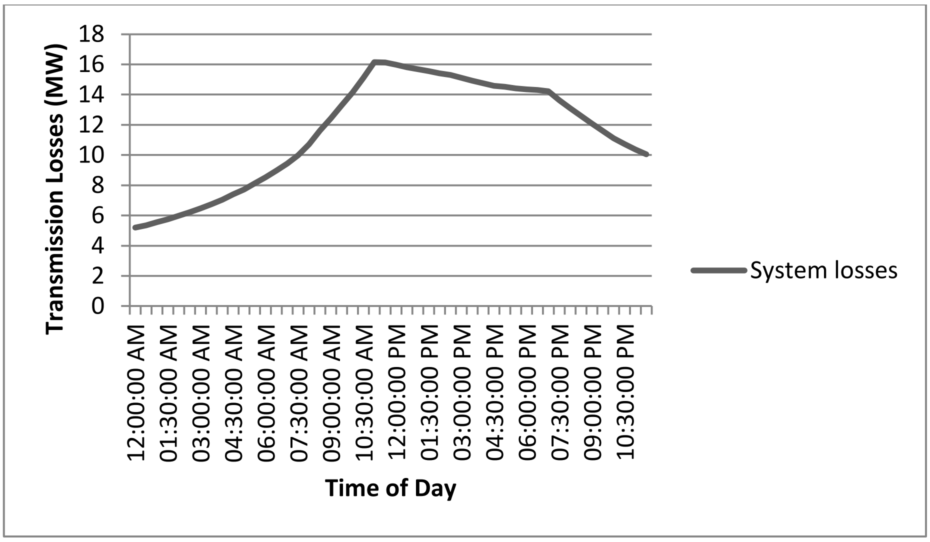

Figure 7.8: Transmission System Losses for the Current Network

[48] Reserves are calculated based on the installed capacity of the generating units. Given that all the units are assumed to be running at all times, the reserves cannot be identified as being hot or cold.

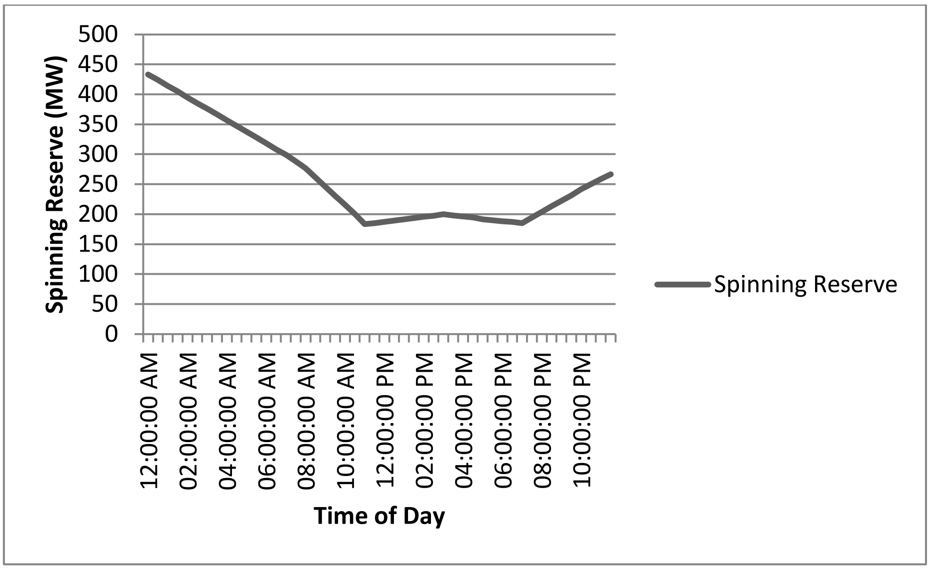

Figure7.9: Spinning Reserves for the Current Network

The load bus voltages were all within range with the exception of 14 instances when the value at the Ocho Rios and Roaring River Buses were at 0.94 pu. These low voltage levels occurred while the loads on these substations were at their peak values.

Additional information on the spread of voltage level at the load buses are shown in Table 7.6.

Table 7.6: Spread of Bus Voltages for the Current Network

Bus Voltage Limit	*Number of Occurrences*
0.94	14
0.95	131
0.97	269
0.98	621
0.99	530
1.01	560
1.02	179

7.2 Increased Load Analysis

Having established the operation of the system, under current loading and generation conditions, the impact of increased loading on the network is determined in this section. The same criteria assessed in section 5.1 are again looked at under these new loading conditions. The system loading used are based on the conditions established in section 4.5.7. The actual years considered are 2008, 2010, 2012, 2015 and 2020. The years 2008 to 2012 were chosen based on RES-E targets for this period as well as 2008 being the reference period.

7.2.1 Bus Voltage Levels

Load Buses

The voltage levels at the load buses, based on load increases between 2008 and 2020 at an annual increase of approximately 2.5%, are shown in Figure7.10.

With the increased system load over the study period, the associated bus voltages were also reduced. The percentage of the buses falling outside of the acceptable tolerance is shown in Figure7.11.

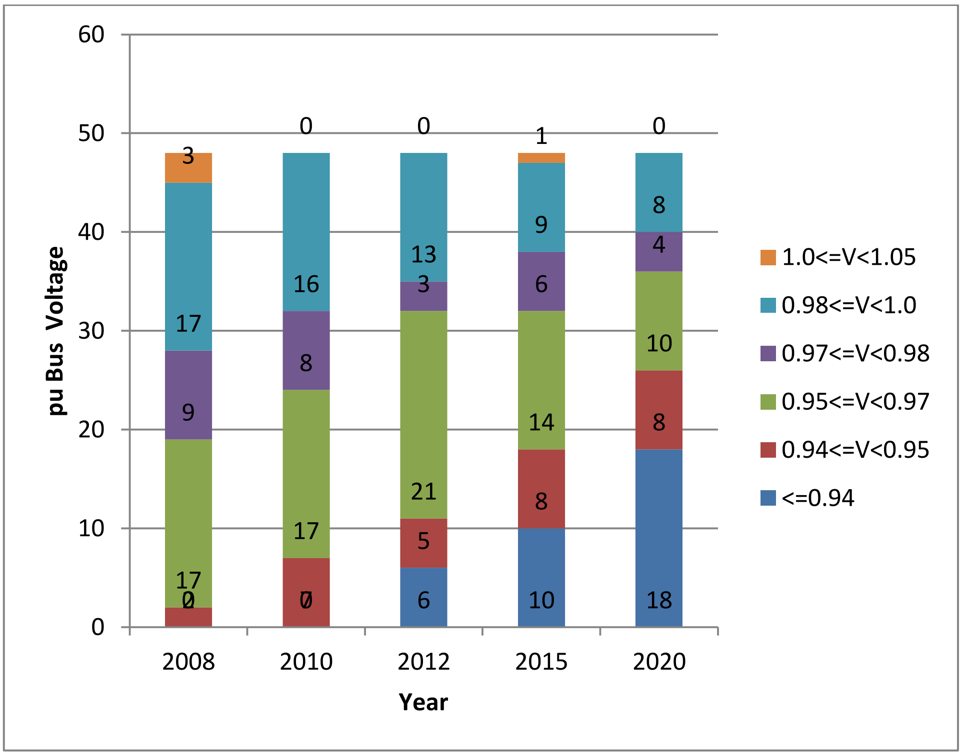

Figure7.10: Load Bus Voltages 2008 to 2020

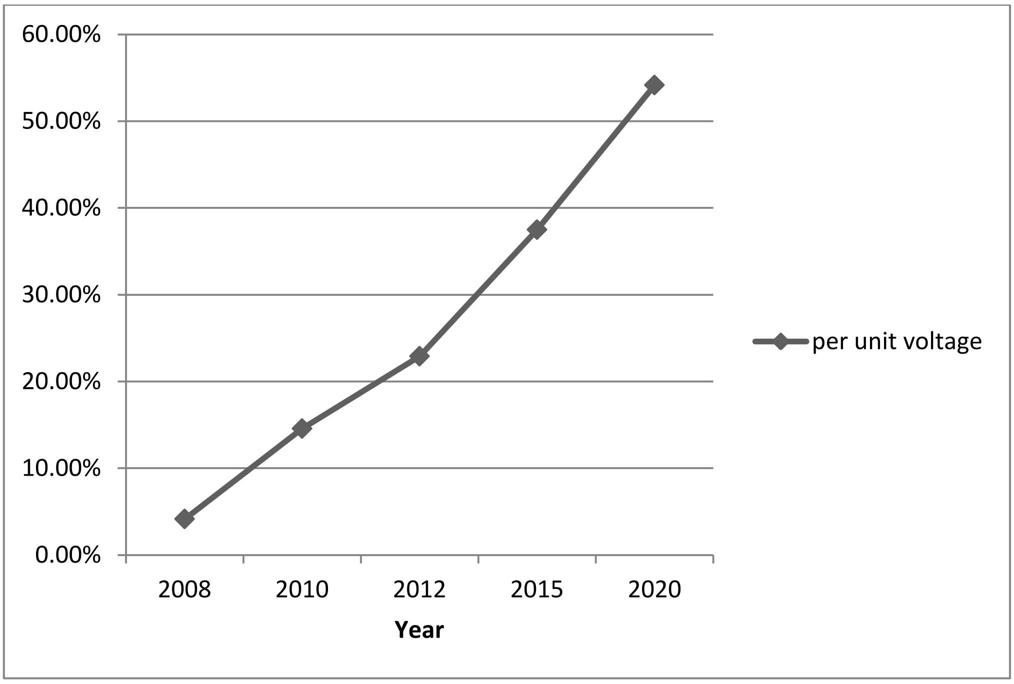

Figure7.11: Percentage of Load Buses with Voltage below Prescribed Level

Generator Buses

Many of the generator bus voltages shows increases in successive years as their output increased to meet the new demand.

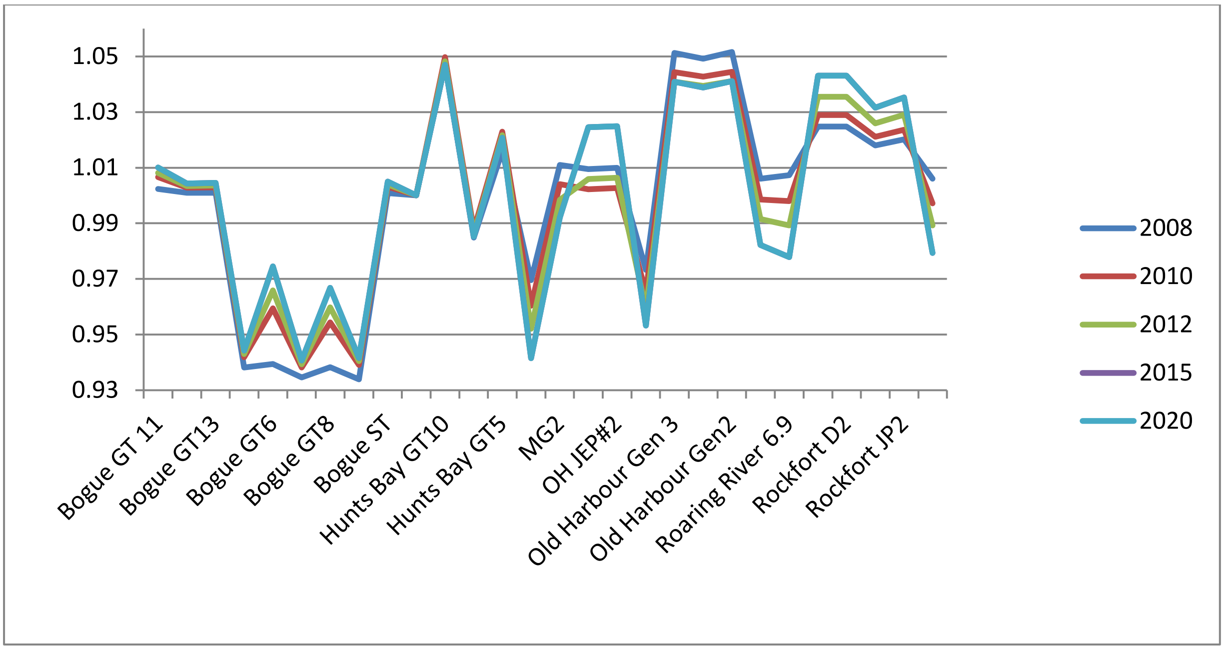

Figure7.12: Generator Bus Voltages 2008 2020

This change was however true only for those units with automatic voltage regulation capability and the requisite capacity to meet the additional reactive power requirement. Other units which were not similarly designated operated at reduced voltages[49].

These changes in voltage on individual generating units resulted, primarily from the need to maintain the system voltage at the controlled buses. The impact of the change is further highlighted in table 5.7 where the voltages at the controlled buses which are supplied, for the most part, by AVR capable units remained virtually constant over the period.

Additionally most of the AVR capable units, although reaching their peak active power limits still had excess reactive power capabilities.

Table 7.7: Per Unit Voltages of Reference Buses Controlled by AVR Capable Generators

Year	**2008**	**2010**	**2012**	**2015**	**2020**
Controlled Buses					
Bogue 69 (BG69)	1.00002	1	1	1.00001	1
Hunts Bay A (HB A)	1.00001	0.9992	0.9977	0.99665	0.99413
Old Harbour 138 (OH138)	1.01002	1.00333	1	1	1
Old Harbour 69 (OH69)	1.00232	0.99387	0.98778	0.98233	0.9698
Old Harbour Gen 4	1.04926	1.0427	1.03935	1.03885	1.03852
Rockfort (RF)	1.00001	1	1	1	0.9982

The Hydroelectric units which are highlighted in Table 5.8 do not have AVR capability. From the data it can be seen that their voltages declined steadily with the increases in load.

[49] Note the interchange between 2008 and 2020 figures in figure 5.12

Table 7.8: Per Unit Voltages of Reference Buses Controlled by Non-AVR Capable Generators

Year	**2008**	**2010**	**2012**	**2015**	**2020**
Controlled Buses					
Lower White River (LWR)	0.9595	0.94983	0.94127	0.93043	0.90896
MG2	1.01108	1.0041	0.99849	0.99207	0.98
RBB	1.00627	0.99855	0.99154	0.98224	0.96459
Roaring River 6.9	1.00761	0.99799	0.98928	0.97786	0.95557
UW2	1.00629	0.99722	0.98926	0.97931	0.95957

7.2.2 Generator Output

The production costs for the steam based generating units are shown in Figure7.13. Based on the load increases in each time period, the Old Harbour generating units numbers G2 and G3 will reach their maximum output in 2012. The other unit reaching its peak from that station is the G1 which reaches full capacity in 2015. While unit G4 has a minimal capacity beyond this period; the Hunts Bay unit, being the slack unit would be required to produce an output significantly beyond its rated maximum output[50].

Figure7.14 which illustrates the operation of the generating station in the western end of the island, highlights the disparity in the production costs associated with the different technologies employed. The combined cycle units are producing at a far better rate of efficiency that the combustion engine units. As a consequence of the disparity in operating costs, these units reach their peak output in 2012.

While not highlighted, the Hydro units are assumed to be running at a fixed output. This of course is based on an assumption that there is little or no variability in rainfall and therefore water flow during the study period. The impact therefore of drought conditions are not considered at this time.

[50] Indicates a generation shortfall

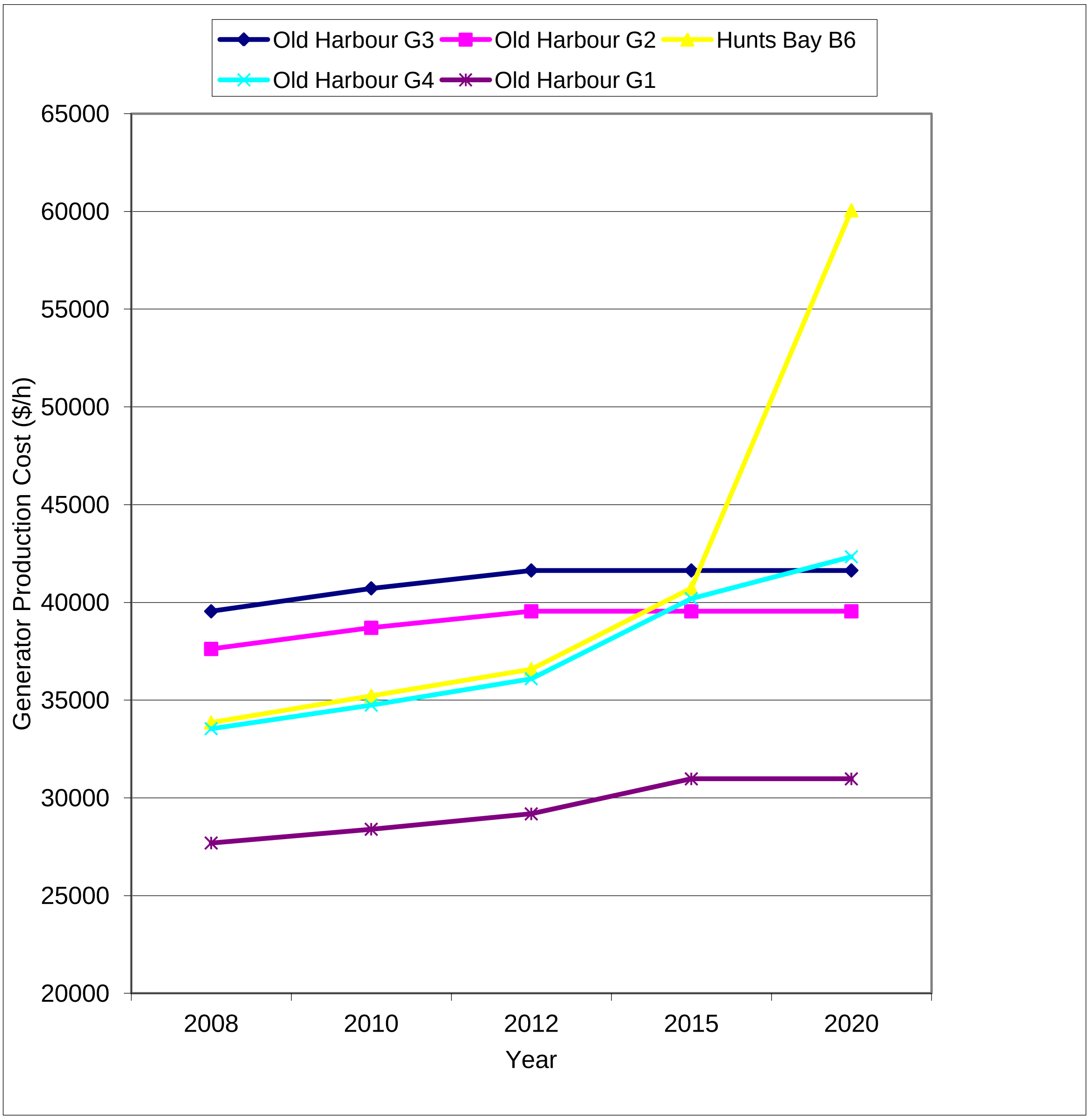

Figure7.13: Production Cost of Steam Generating Units between 2008 and 2020

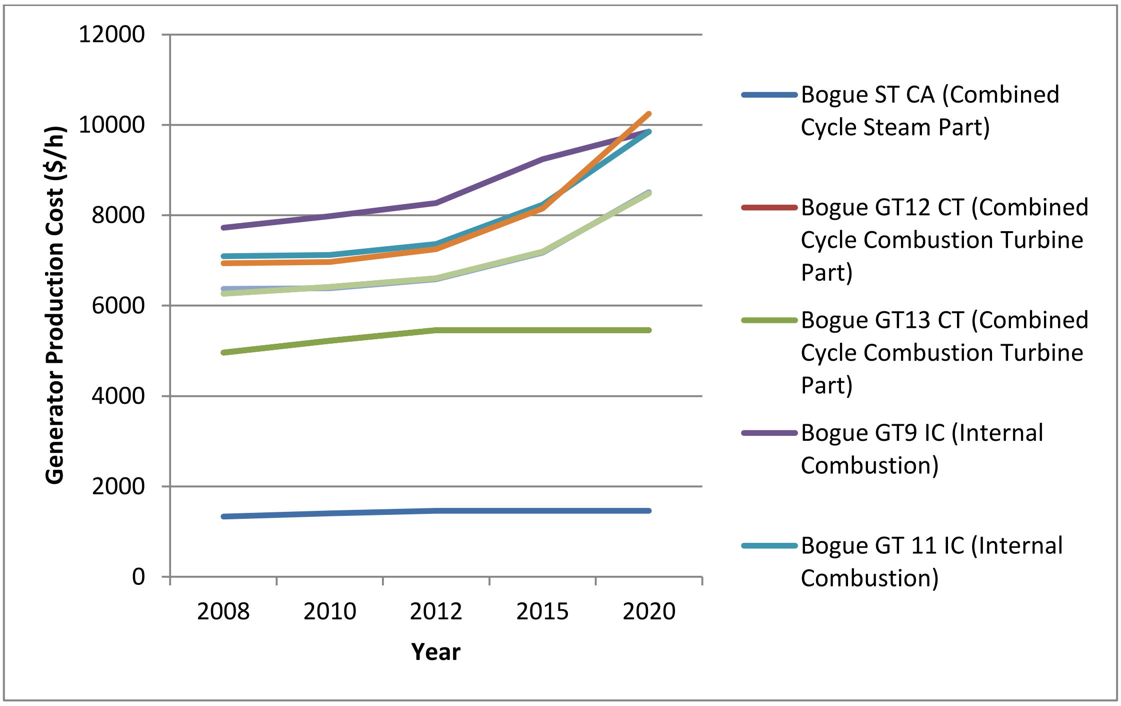

Figure7.14: Generation cost for Fossil Fuelled Internal Combustion Engines and Combined Cycle Plant

7.2.3 Fault Levels

The figure below shows the current and predicted fault levels at the system load buses between 2008 and 2020. With an overall increase of Thirty Four percent increase in the system loads, the largest increase in fault level was approximately 2.7%. This increase occurred at the Rockfort (RF) busbar.

Based on a review of the data, buses in the immediate vicinity of the generating facilities or those which had significantly high load demands showed increased fault levels. These buses and the corresponding percent increase in fault levels are shown in Table 7.9.

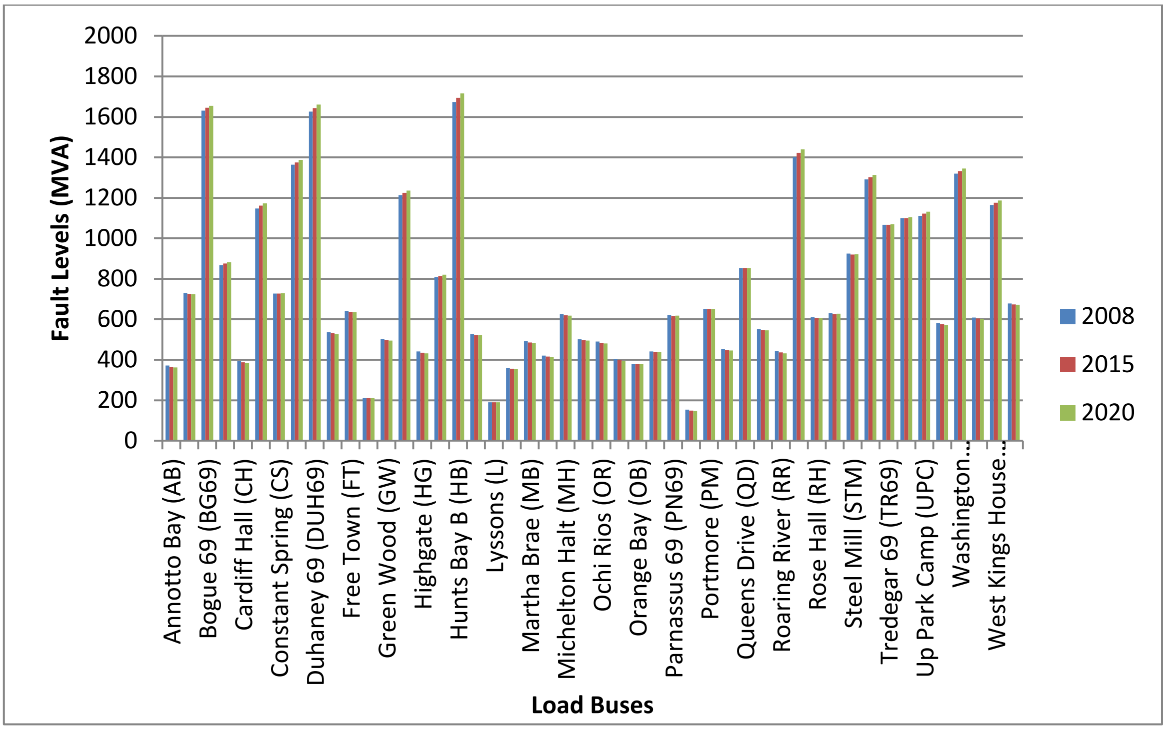

Figure 7.15: Fault Levels at Load Buses for the Years 2008, 2015 and 2020

Table 7.9: Load Buses having increased Fault Levels

Bus Name	**Fault Level 2008**	**Fault Level 2015**	**Fault Level 2020**	**Percent Increase**
Bogue 69 (BG69)	1631	1644	1654	1.397997
Cane River (CR)	867	875	881	1.622463
Cement Company	1148	1162	1173	2.195841
Constant Spring (CS)	727	727	729	0.262657
Denoes and Geddes (D&G)	1364	1375	1387	1.637047
Duhaney 69 (DUH69)	1627	1643	1661	2.128457
Greenwich Road (GR)	1214	1225	1236	1.791145
Hope (HP)	809	815	820	1.360211
Hunts Bay B (HB)	1674	1694	1717	2.542978
Rockfort (RF)	**1402**	**1423**	**1440**	**2.702426**
Three Miles (TM)	1291	1302	1314	1.766372
Tredegar 69 (TR69)	1067	1067	1071	0.328957
Twickenham Park (TWP)	1100	1100	1105	0.458013
Up Park Camp (UPC)	1110	1122	1132	1.966278
Washington Boulevard (WB)	1320	1332	1345	1.890602
West Kings House Road (WKHR)	1165	1176	1187	1.886293

7.2.4 System Loading

The transformer loading shown in the figure below; highlights the fact that the vast majority of the units operated within their rated limits. Those shown as overloaded in 2008 and 2010 are the units at the Tredegar Park and Lower White River, which are already referenced. The overloaded conditions highlighted in the successive years resulted, primarily, from generators producing greater than usual reactive power output, thereby causing the MVA ratings to be exceeded.

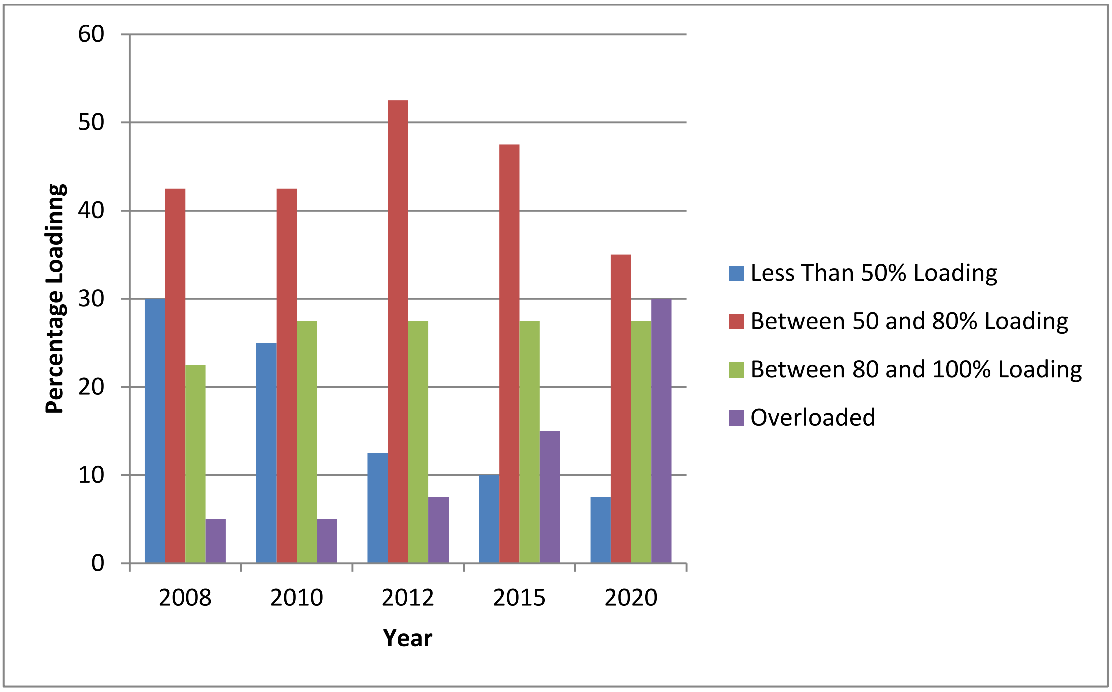

Figure7.16: Transformer Percentage Loading 2008 – 2020

Despite the loading aberration highlighted in the year 2020 model, the transmission lines in the network continues to operate significantly below their capacities. Figure7.17 shows that the maximum loading of transmission lines within the network was sixteen percent (16%).

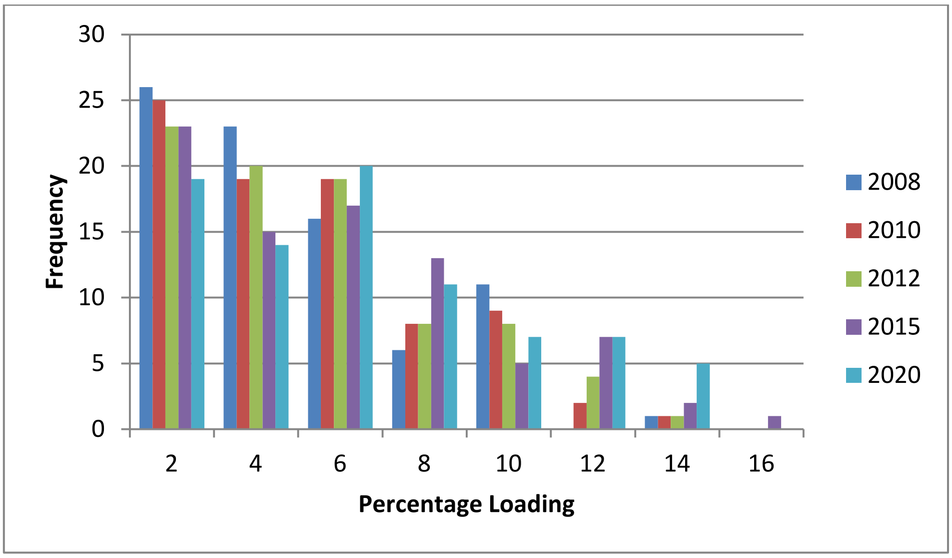

Figure7.17: Transmission Line Percentage Loading 2008-2020

7.2.5 System Contingencies

Contingency studies were conducted separately for generators, transmission lines and transformers for each of the load periods of the study. The numbers of contingencies for each equipment type were; generators – 29, lines – 83 and transformers - 42

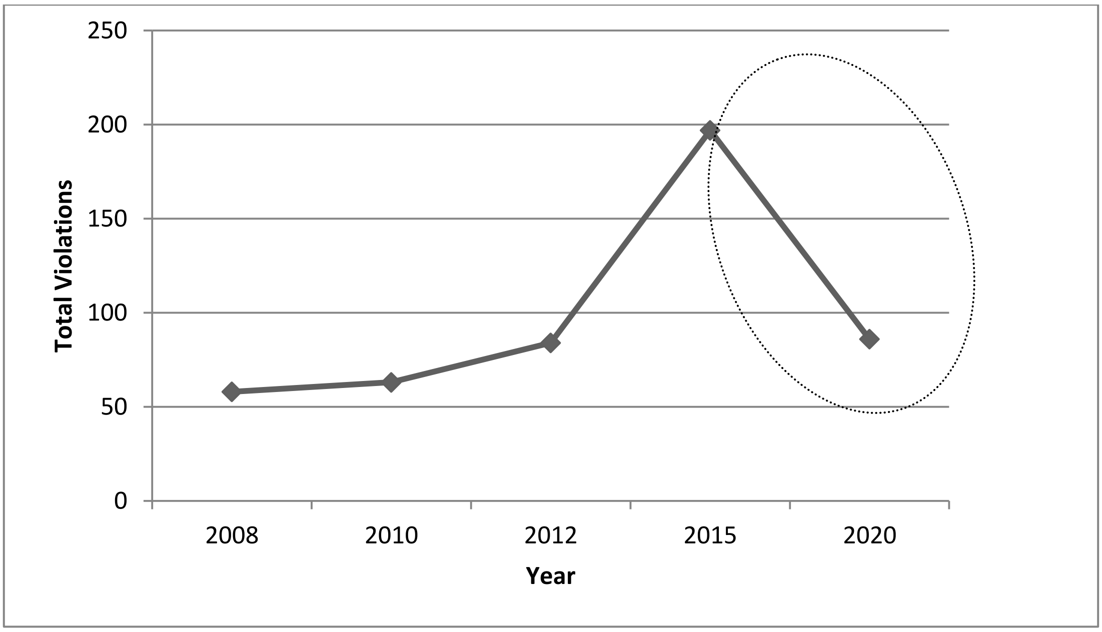

Figure7.18: Transformer Violations Resulting from Generator Contingencies

As was expected the number of transformer violations resulting from generator contingencies increased with increased system loading. The reduction between 2015 and 2020, as shown in Figure7.18 resulted from a number of unsolved contingencies[51].

The violations highlighted are transformer capacity violations. The actual violations occurring on the network are shown in the table below.

Table 7.10: Transformer Violations Resulting from Generator Contingencies

Violations	**2008**	**2010**	**2012**	**2015**	**2020**
Transformer Connection					
Bellevue 138 to Bellevue 69		**1**	**15**	**29**	**7**
Bogue 69 to Bogue GT9					**7**
Bogue 69 to Bogue GT8					**7**
Bogue 69 to Bogue GT6					**7**
Bogue 69 to Bogue GT7					**1**
Hunts Bay A to Hunts Bay B6	**6**	**10**	**11**	**15**	**7**
Hunts Bay A to Hunts Bay GT5				**28**	**7**
Hunts Bay A to Hunts Bay GT10				**28**	**7**
Lower White River to LW	**28**	**28**	**28**	**28**	**6**
Old Harbour 138 to Old Harbour 69	**1**	**1**	**1**	**2**	**7**
Old Harbour 69 to Old Harbour Gen 1				**28**	**7**
Roaring River to Roaring River 6.9	**1**	**1**		**1**	**2**
Rockfort to Rockfort D1			**1**	**4**	**4**
Rockfort to Rockfort D2			**1**	**4**	**3**
Tredegar 138 to Tredegar 69	**21**	**21**	**26**	**29**	**7**
Old Harbour 138 to Old Harbour Gen 4	**1**	**1**	**1**	**1**	

No bus violations resulted for any generator contingency apart from those tested for 2020.

The total violations for Transformer and Transmission Line contingencies are shown in figures 7.19 to 7.22. Tables showing the actual violations and corresponding contingencies are shown in appendix C.

[51] Unsolved contingencies occurred due to the simple inability of the available online generation to meet the system demand. This condition is represented by a system blackout.

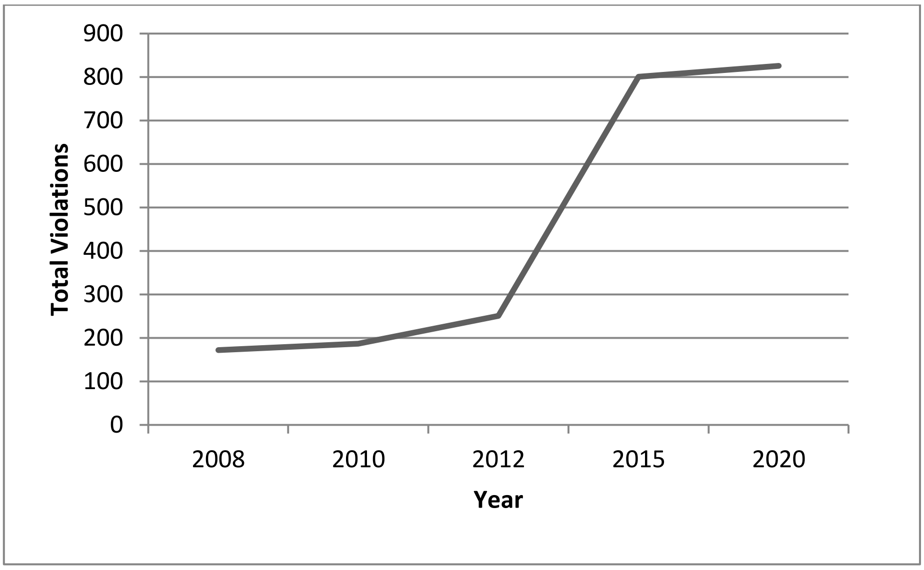

Figure7.19: Line Violations Resulting from Line Contingencies

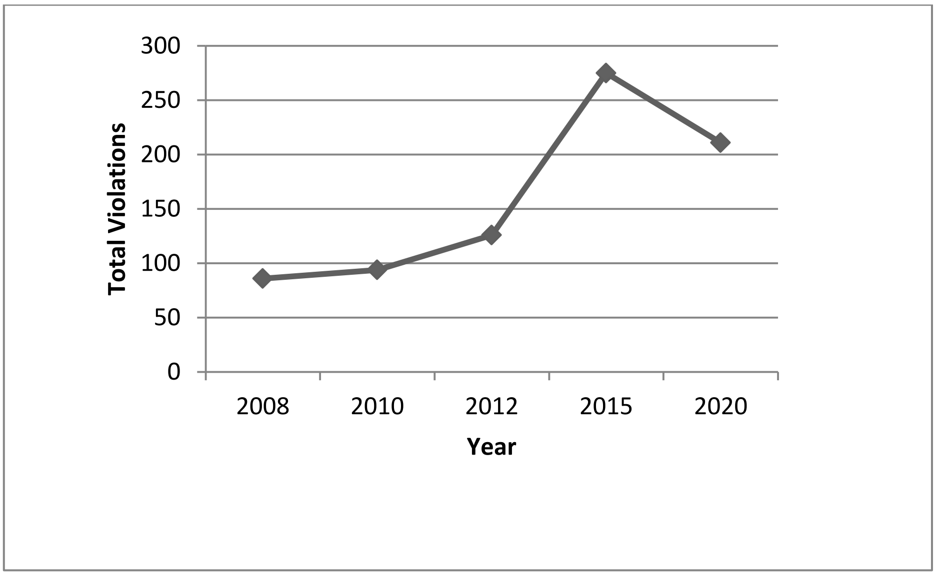

Figure7.20: Line Violations from Transformer Contingencies

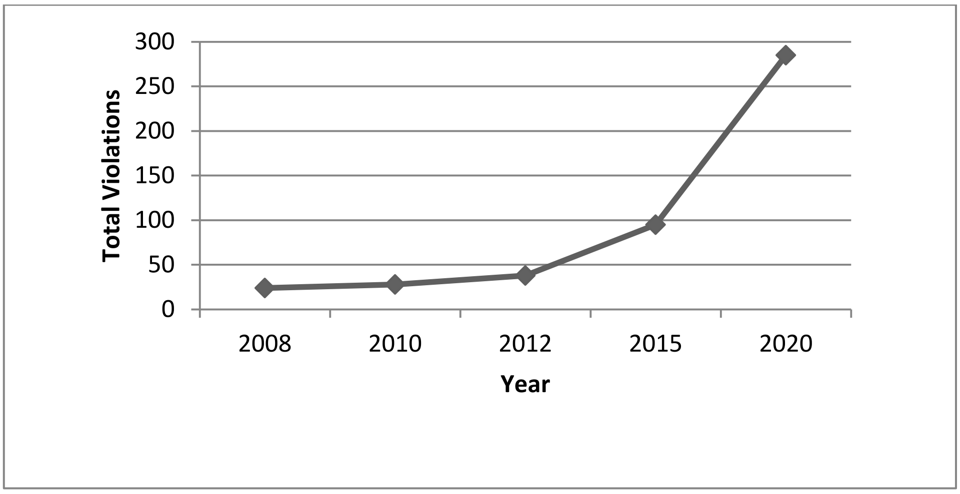

Figure7.21: Bus Voltage Violations from Line Contingencies

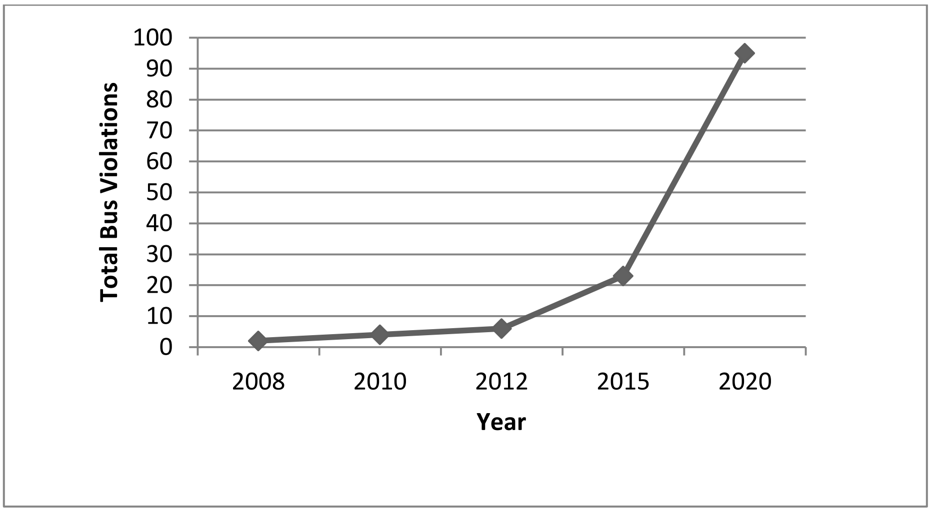

Figure7.22: Bus Voltage Violations from Transformer Contingencies

7.2.6 Daily Load Analysis

The total annual energy produced over the study period increased from 4.89 to 6.63 TWh. The individual breakdown is shown in Figure7.23 below.

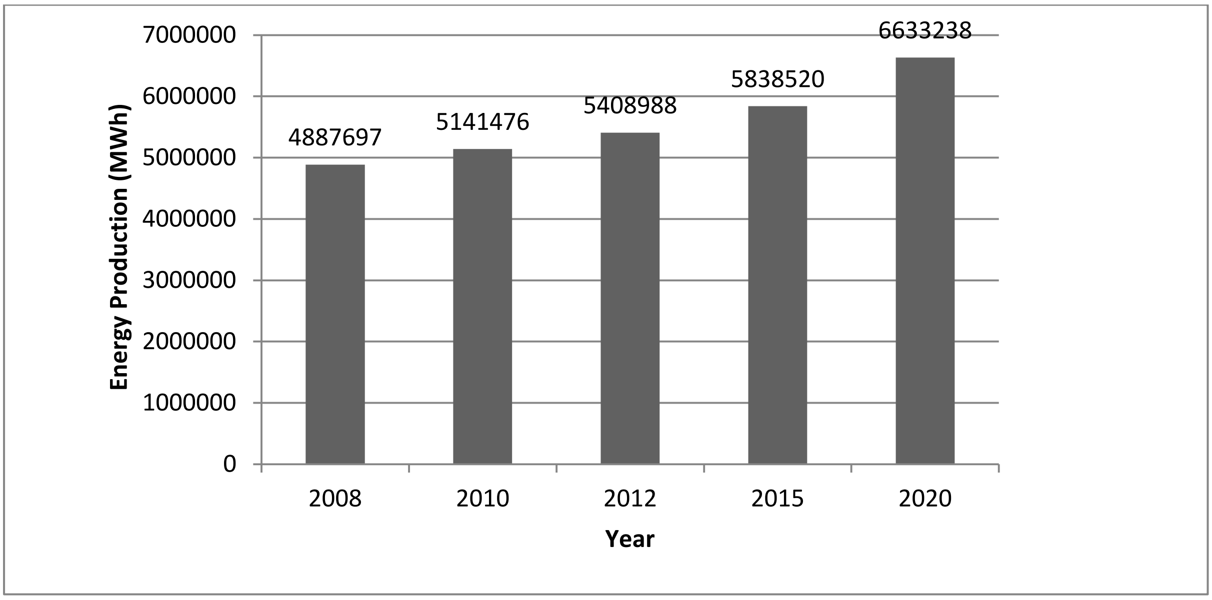

Figure7.23: Total Energy Production

The corresponding transmission system losses are also highlighted below.

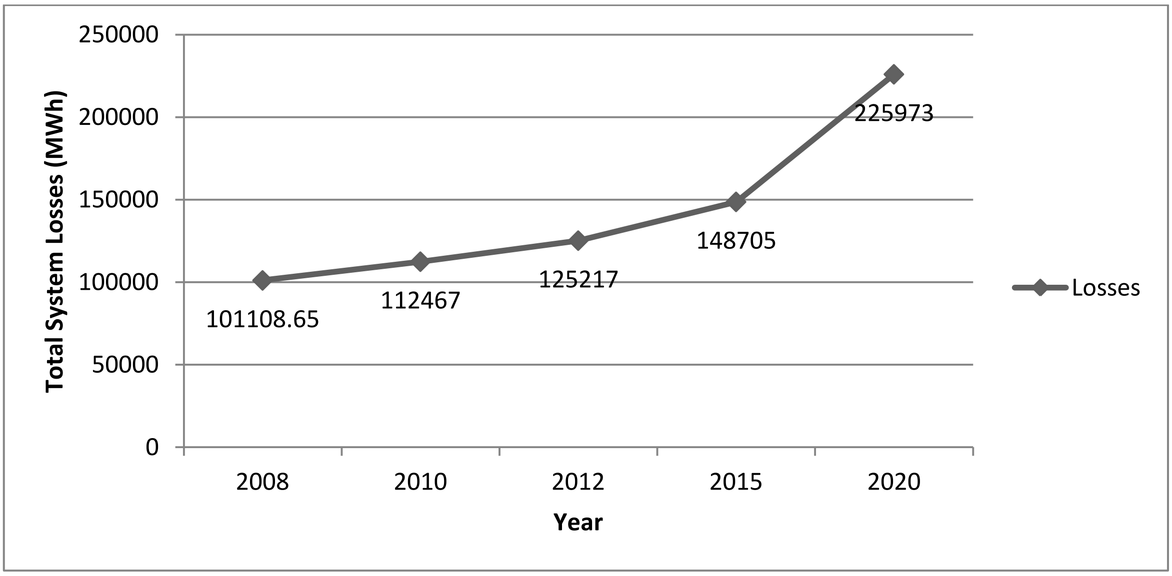

Figure7.24: Transmission System Losses

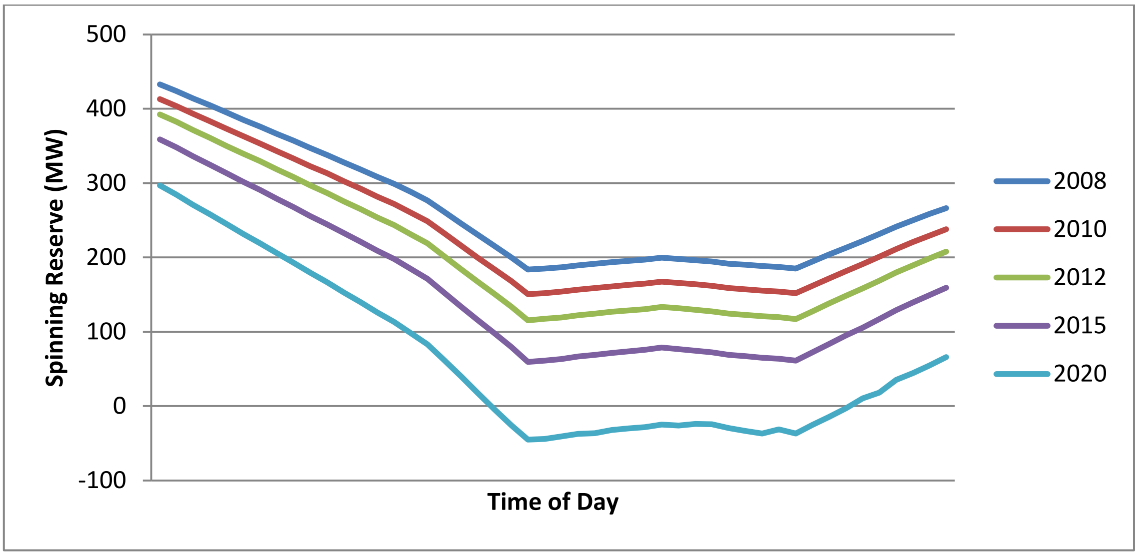

Figure7.25: System Spinning Reserve

Figure 7.25 is the system's reserve margins for the successive load demands under consideration. The fact that the reserve margin curve for the year 2020 is negative signifies the need for additional generation capacity to meet the load demand.

Bus Voltages

Table 7.11 shows the spread of the busbar voltages in a 24 hr period, for each of the study periods. While the number of load buses having voltage values below the prescribed minimum increased in successive years, the vast majority remained within the prescribed limits.

Table 7.11: Spread of Busbar Voltages Resulting From Increased System Loading

	2008	2010	2012	2015	2020
Busbar Voltage Limit	Frequency				
0.94	14	56	154	393	1032
0.95	131	241	284	285	288
0.97	269	288	316	378	235
0.98	621	624	647	666	401
0.99	530	539	498	355	169
1.01	560	447	351	220	137
1.02	179	109	54	7	40

Conclusion

As was expected, there was a general decline in the operational standards of the system. Among these were declines in bus voltages, transformers reaching close to their operating limits etc. Of note also is the fact that the loading as described for 2020 exceeded any acceptable operating point and will therefore not be considered for any further consideration. The limiting loading is therefore taken as the demand representing 2015. With this in mind the assessment of the system's operation in relation to embedded generation is determined in the next chapter.

CHAPTER 8

System Capacity Results and Comparative Analysis with Embedded Generation

Chapter 8 is comparative analysis of the impact of embedded generation on the system with respect to increased loading. The analysis is made based on the peak demand as well as the demand spread over 24 hrs.

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Introduction

Having analysed the operation of the network at the various loading levels representing the years 2008 to 2020; it was necessary to determine the impact of the inclusion of the embedded generators. The renewable targets outlined in chapter one indicated targets of 5.6, 11 and 12.5% of installed capacity in 2008, 2012 and 2015 respectively. Notwithstanding these targets, the analysis was conducted based on each of five areas being supplied by installed capacities of ten (10) and twenty (20) megawatts. This corresponds to a total installed wind generation capacity of 50 and 100MW for the Island.

The current loading level of 620MW represented by 2008 and future loading of 737MW represented by 2015 are used for the basis of the analysis. The 2015 loading was used as the upper limit as based on the data, it represented the limiting value where the system operated normally albeit with severely depressed bus voltages among other operational breaches.
In chapter 3 it was established that the peak load occurred in the evening at approximately 1900 Hrs. This time however does not correspond with the maximum output of the wind turbines. The turbine output corresponding to the time of the peak load for each of the study areas is therefore used.

Embedded Generator Analysis

8.1 EG Impact on Load Bus Voltages

From Figure 8.1 it can be seen that the bus voltages all improved with the injection of the generators. As the injection increased so did the bus voltages.
Whereas for the base system where two bus voltages fell below the tolerance level, none were outside these limits when operated with the EG connected. Although not clearly highlighted the buses showing the largest level voltage increase were those in the vicinity of the wind generators.
Given that the wind turbines were fitted with capacitor banks it was important to determine if the Var support from the capacitors was the real reason for the voltage improvement. While the system without capacitor support coincided with the voltages without EG; there were declines in some areas. On closer analysis it showed that many of these occurrences were in the vicinity of the wind farms.

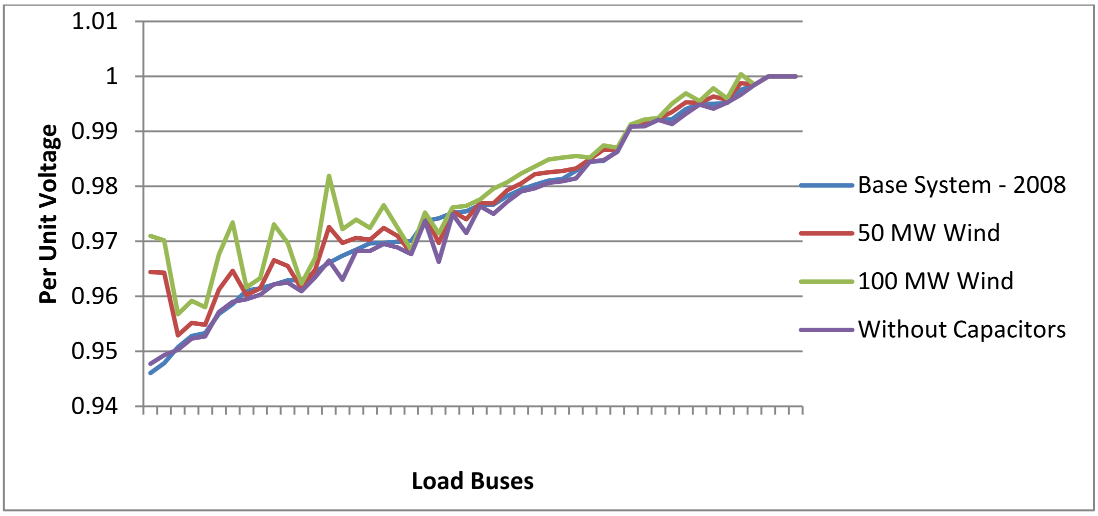

Figure 8.1: Load Bus Voltages in the Network for the Reference System with Dispersed Wind Generation

This is indicative of the fact that the turbines were themselves now absorbing reactive power from the network. While the capacitors cannot be full y discounted as having an impact, their outputs were used to directly maintain the wind turbine bus voltage between the limits of 1 and 0.95 per unit.

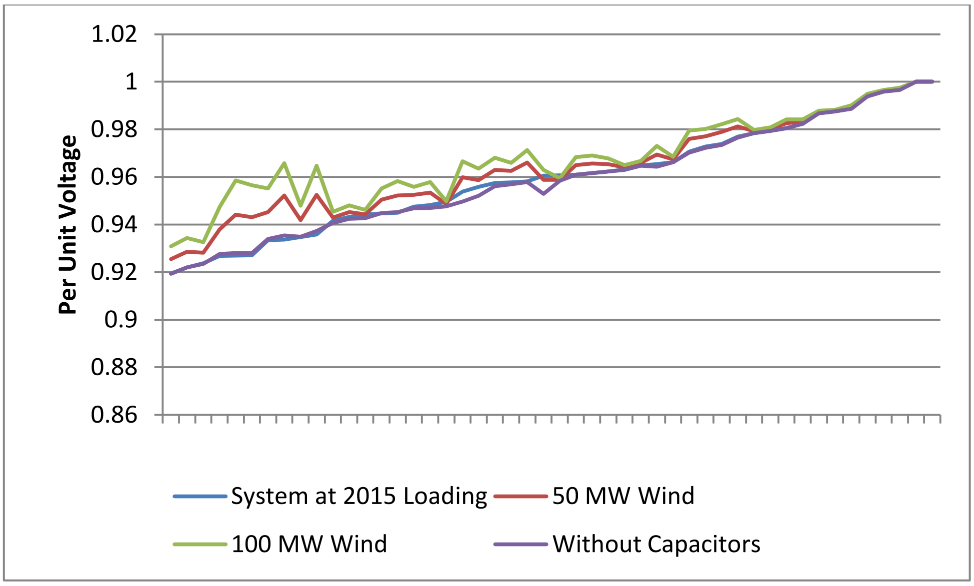

Figure 8.2: Load Bus Voltages in the Network at Increased Load with Dispersed Wind Generation

With the increased loading there was still improvement in the load bus voltages throughout the network. Whereas 37.5% of the buses had voltages below 0.95 per unit when the network operated without EG; only 25% fell in this category with 50MW falling further to 18.75% when 100MW was injected.

Table 8.1: Per Unit Voltage of the Controlled Buses for Increased Load with Dispersed Wind Generation

Controlled Bus	**2015-Reference**	**50MW Wind**	**100MW Wind**
Bogue 69 (BG69)	1.00001	1.00002	1.00001
Hunts Bay A (HB A)	0.99665	0.99719	0.99749
Old Harbour 138 (OH138)	1	1.00001	1
Old Harbour 69 (OH69)	0.98233	0.9867	0.98965
Old Harbour Gen 4	1.03885	1.03909	1.03919
Rockfort (RF)	1	1	1

In the context of the operation of a power system the controlled buses highlighted can be regarded as operating at a fixed voltage. However, from the results in the table above, it has been shown that these voltages improved with increased EG.

8.2 Line and Transformer Loading

While not significant, the loading of transformers within the network declined with increased EG input.

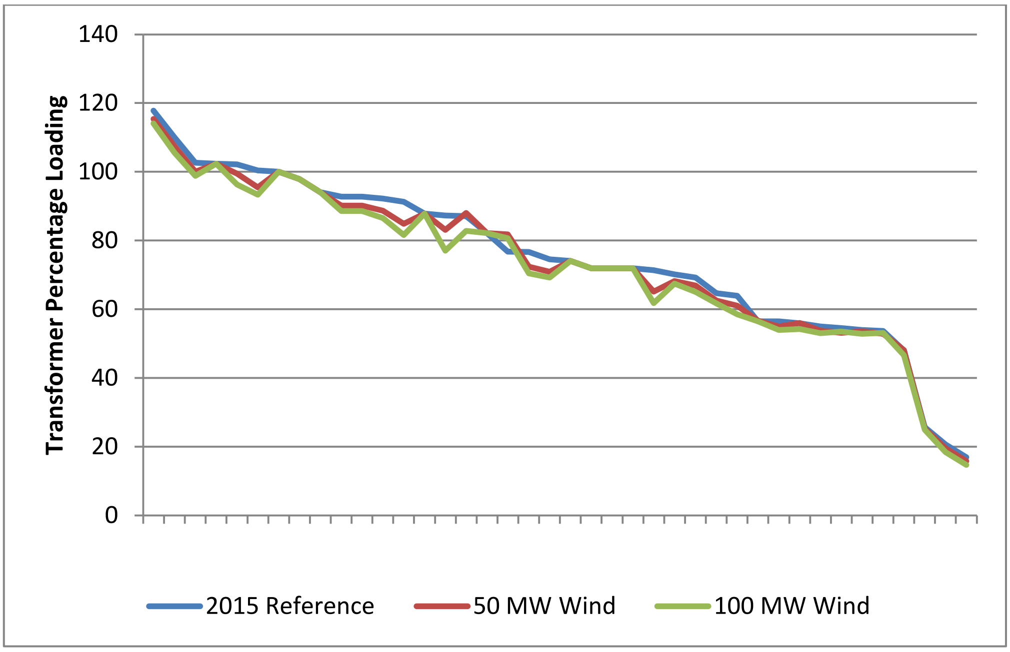

Figure 8.3: Transformer Percentage Loading at 2015 for Dispersed Wind Generation

The number of overloaded units within the network declined as the amount of EG increased.

8.3 Fault Levels

Table 5.2 highlight significantly increased fault levels for the substations connected directly to the wind farms. Increase in fault levels at the other load buses was much lower than those occurring at these associated buses.

The average increase in the fault levels for substations connected to the wind farms is 20%; however the increase at the Lyssons substation, of 36%, was substantially higher than the others. This difference was noted in both the instance of initial inclusion of EG as well as with increased EG input. Of note was the fact that this substation was the only one of the five which was supplied from a radial line.

Table 8.2: Fault Levels at Load Buses for System Loading in 2015 with Dispersed Wind

Substation	Fault Levels Without Wind Input (MVA)	Fault Levels with 50 MW Wind Input (MVA)	Fault Levels with 100 MW Wind Input (MVA)	Percent Increase (0-50MW)	Percent Increase (50 -100MW)
Bogue 69 (BG69)	1644.3	**1709**	**1749**	**4**	2.34
Cane River (CR)	874.9	**931**	**964**	**6**	3.50
Cement Company	1161.6	**1214**	**1244**	**5**	2.45
Constant Spring (CS)	727	**740**	**747**	**2**	1.02
Denoes and Geddes (D&G)	1374.7	**1418**	**1443**	**3**	1.77
Duhaney 69 (DUH69)	1642.9	**1709**	**1748**	**4**	2.30
Greenwich Road (GR)	1225	**1260**	**1280**	**3**	1.57
Hope (HP)	814.6	**843**	**859**	**3**	1.88
Hunts Bay B (HB)	1694	**1756**	**1792**	**4**	2.02
Rockfort (RF)	1422.6	**1480**	**1513**	**4**	2.20
Three Miles (TM)	1301.7	**1342**	**1364**	**3**	1.69
Tredegar 69 (TR69)	1066.7	**1126**	**1165**	**6**	3.50
Twickenham Park (TWP)	1100.4	**1149**	**1180**	**4**	2.72
Up Park Camp (UPC)	1121.8	**1158**	**1178**	**3**	1.76
Washington Boulevard (WB)	1331.9	**1378**	**1404**	**3**	1.92
West Kings House Road (WKHR)	1176.1	**1217**	**1240**	**3**	1.91

With respect to loading at the substations, the Annotto Bay station was the most lightly loaded, while the Orange bay station carried the heaviest load. Both the Orange Bay and the Lyssons stations are situated in close proximity to major generation stations.

Based on the aforementioned facts it is clear that the connection to a radial line is the main factor responsible for the significant increase in the fault level.

Table 8.3: Faults Levels at the Load Buses Connected Directly to the Wind Farms

Substation - Load Buses Connected Directly to Wind Farms	Fault Levels Without Wind Input (MVA)	Fault Levels with 50 MW Wind Input (MVA)	Fault Levels with 100 MW Wind Input (MVA)	Percent Increase **in Fault Level** (0-50MW)	Percent Increase **in Fault Level** (50 - 100MW)
Annotto Bay (AB)	366	**435**	**494**	**19**	13.5
Lyssons (L)	189.6	**257**	**314**	**36**	22.2
MonyMusk (MM)	496	**574**	**636**	**16**	10.8
Orange Bay (OB)	377	**448**	**512**	**19**	14.2
Spur Tree 69 (ST69)	626	**710**	**776**	**13**	9.3

8.4 Generator Output

As would be expected, the output of the generators used prior to the inclusion of the wind turbines decreased. Additionally, the transmission system losses were reduced with an increase in the quantity of wind generated energy injected.

Table 8.4: Output of Non-Wind Generators and Transmission System Losses

	Generator Output (MW)	Transmission System Losses (MW)
2008 Reference	634.74	14.74
2008 with 50MW Wind	624.71	13.86
2008 with 100MW Wind	615.01	13.38
2015 Reference	758.67	21.7
2015 with 50MW Wind	748.86	20.6
2015 with 100MW Wind	738.51	19.82

8.5 System Contingencies

Violations resulting from the contingencies considered, all declined with the inclusion of EG.

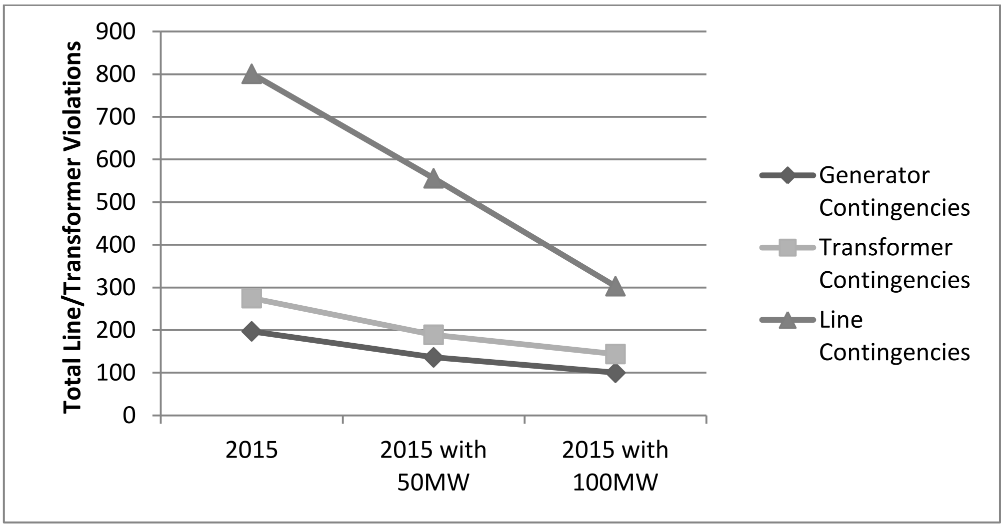

Figure 8.4: Line/Transformer Violations for 2015 Loading with Varying EG Input

Most significant were the declines in the line/transformer violations which declined between 30 and 62% with the inclusion of 50 and 100MW respectively. Though not disaggregated, all the violations recorded, occurred in the power transformers.

Both figures also highlight the fact that the line contingencies resulted in the largest number of violations for transformers and buses alike; this was as a result of the need to reroute power to supply the system loads. However this is where the largest decline was observed given that the more dispersed generation was able to provide supply, in part, at the points of demand.

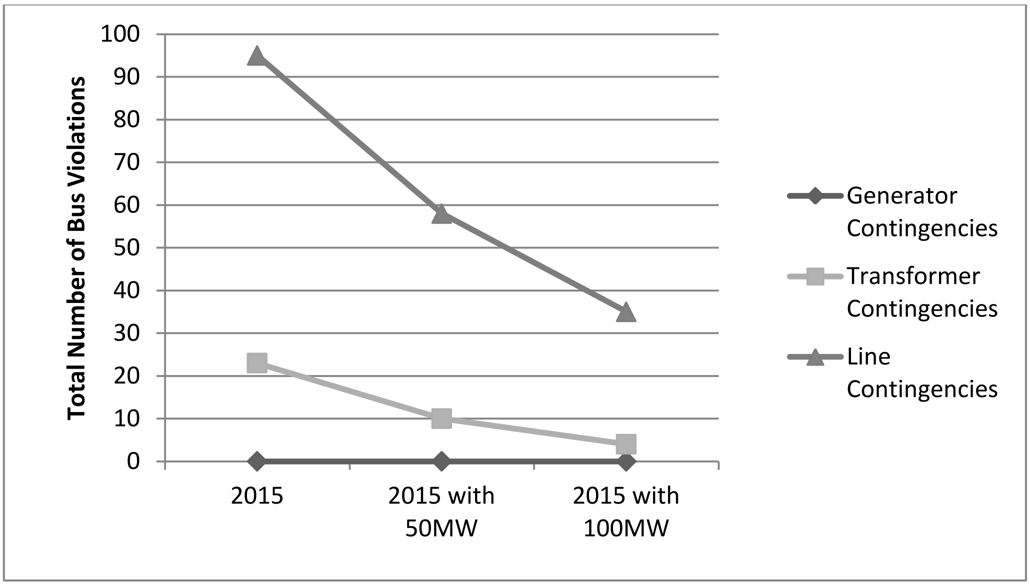

Figure 8.5: Busbar Voltage Violations for 2015 Loading with Varying EG Input

8.6 Daily Load Analysis

The daily load analysis was conducted for 2008 and 2015 loading.

Table 8.5: Energy Consumption Comparison for Varying Loads and EG Input

	Annual Energy Consumption (MWh)	Annual System Losses (MWh)
2008 Reference	4,887,697	101,109
2008 With 50MW Wind	4,881,300	94,670
2008 With 100MW Wind	4,879,092	92,345
2015 Reference	5,838,520	148,705
2015 With 50MW Wind	5,832,622	142,682
2015 With 100MW Wind	5,828,493	138,486

From the table it can be seen that with increased EG input the total energy required to supply the system load was reduced. Concomitantly the losses in the system were also reduced. The figure below highlights the fact that the amount by which the generated energy was reduced was approximately equal to the level of reduction in the system's transmission losses.

The generation shown is the total output of all the generating units inclusive the wind turbines. This indicates that the reduction in green house gasses is helped by not only reducing the total energy required but by also using non-fossil based generation. The total additional renewable energy input from the wind turbines are 88,950.50 MWh and 177,901.00 MWh when using 50 MW and 100 MW installed capacity farms respectively. This additional capacity also supported the system's spinning reserve.[52]

[52] Notwithstanding the fact that the spinning reserve was assessed for increased system loading, this was not considered necessary given that the additional capacity is not considered as firm capacity. The hot spinning

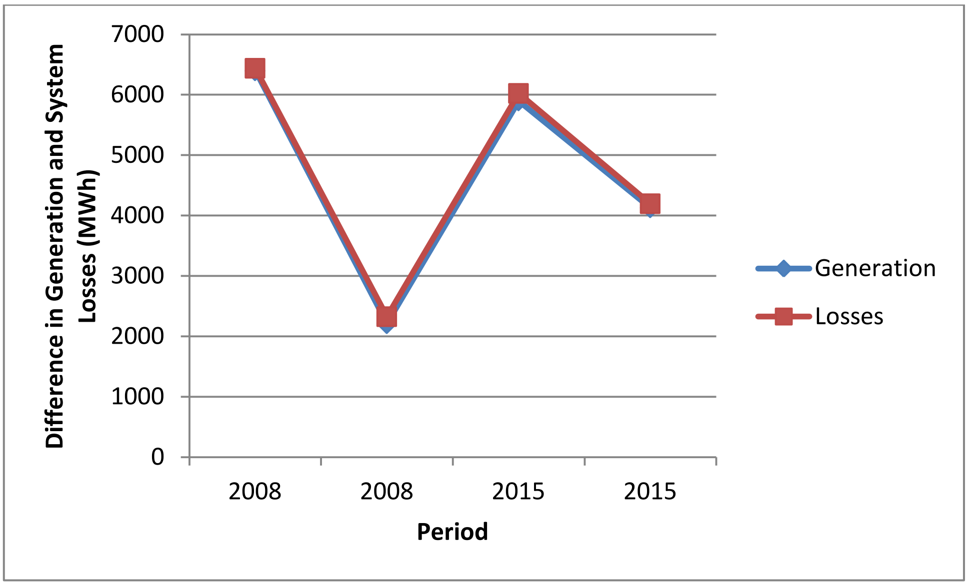

Figure 8.6: Comparison of the Change in Generation Output and Changes in System Losses

Bus Voltages

The spread of the bus voltages shown in the tables below, highlights improvement with increased input from EG.

Table 8.6: Bus Voltage Distribution for 2008 Loading and Varying EG Input

Bus Voltage	*Number of Occurrences Within 24Hour Period*	*10MW*	*20MW*
0.94	14	0	0
0.95	131	46	32
0.97	269	189	165
0.98	621	791	834
0.99	530	607	596
1.01	560	533	533
1.02	179	138	144

reserve would therefore increase by the amount of wind energy being supplied to the system minus the reduction in the system losses.

Table 8.7: Bus Voltage Distribution for 2015 Loading and Varying EG Input

Bus Voltage	***Number of Occurrences Within 24Hour Period***	***10MW***	***20MW***
0.94	393	163	128
0.95	285	206	218
0.97	378	372	386
0.98	666	957	985
0.99	355	405	393
1.01	220	201	194
1.02	7	0	0

While the data was not disaggregated to determine the actual busbars that had voltage improvements, the fact that it occurred in such significant numbers is satisfactory.

CHAPTER 9

Results and Analysis for the Siting of Embedded Generators

Chapter nine presents the results and analysis for the siting of the embedded generators. While siting is the main consideration, the capacity impact at the different identified sites is also presented. Similar to chapter eight, the criteria for assessment were the bus voltage, line and transformer loadings, system output and losses.

Introduction

Having established the impact of the magnitude of embedded generation on the power network, it was now essential to determine the impact of the location of such plants. Given that the impact on

1. Fault levels in individual substations
2. Increasing load demand and
3. Contingencies

have been well established, the effect of the other criteria are therefore considered. The remaining criteria to be assessed are:

1. Bus Voltages – both for peak and 24 hour operation
2. Line and transformer Loading
3. System Output and Losses

This assessment is made based on the injection of wind energy into each of the five areas, in the three regions, identified in chapter 3. The full 50 and 100MW capacity input are inserted successively in each of the areas and the results analyzed. The system load used corresponds to that represented by 2015 as established in chapter 2.

Load Bus Voltages

Figure 9.1 shows the change in load bus voltages resulting from EG input of 50MW in each of the five regions. Although not clearly established in the figure, the spikes for the Lucea and Morant Point occurred at the busbars in their immediate vicinity. While in general there was improvement in the bus voltages, no clear distinction can be made in relation to injection in a particular area.

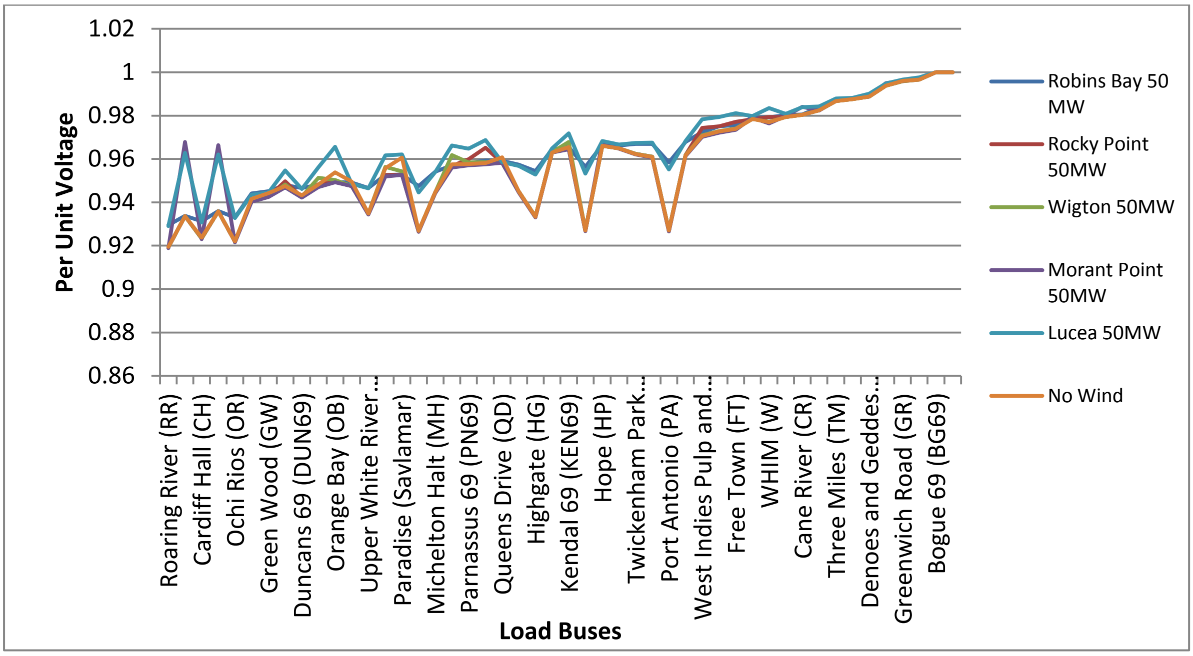

Figure 9.1: Load Bus Voltages with Wind Energy Input of 50MW in Successive Regions

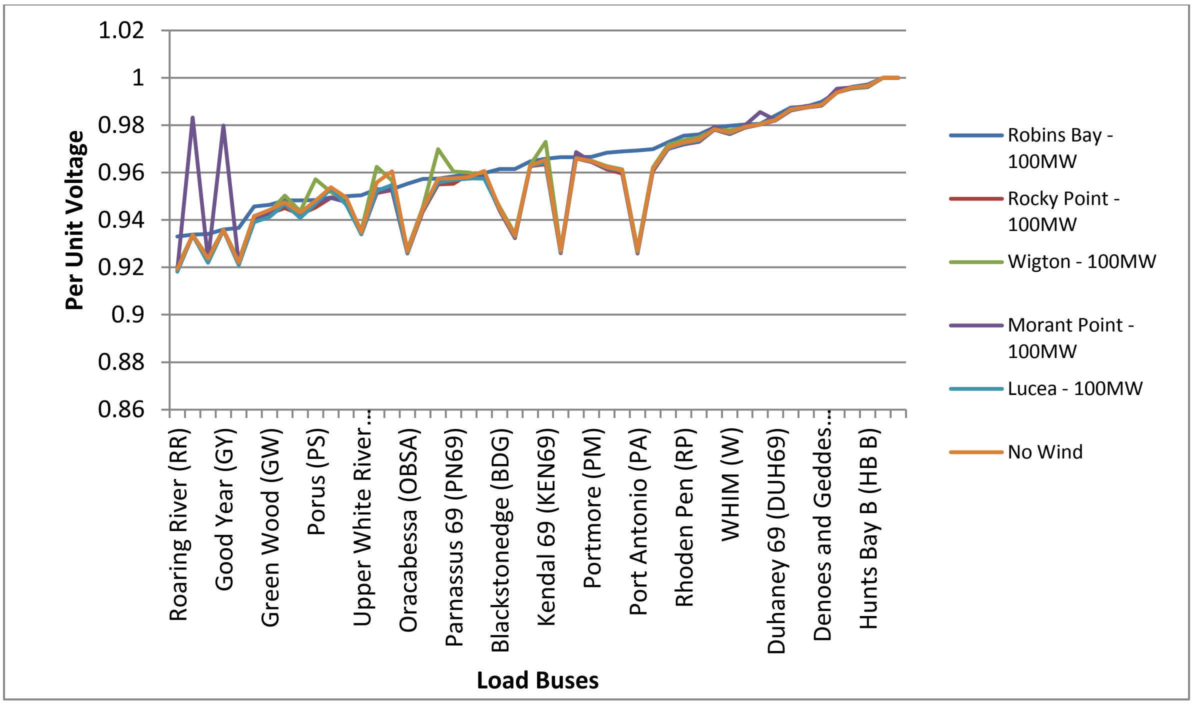

Figure 9.2: Load Bus Voltages with Wind Energy Input of 100MW in Successive Regions

By increasing the input to 100MW, as shown in Figure 9.2, there was only a marginal improvement in the bus voltage levels. From the two figures, the input at the Robins Bay farm, results in the most uniform improvement across the network.

Table 9.1: Distribution of Load Voltages across the Network with Wind Energy Input of 50MW in the Five Regions

Voltage Range	*No Wind Input*	*Lucea*	*Morant Point*	*Wigton*	*Rocky Point*	*Robins Bay*	*Dispersed Generation*
0.94	17	8	16	16	18	13	**1**
0.95	14	22	15	15	13	18	**17**
0.97	6	4	6	6	6	5	**9**
0.98	9	11	10	9	10	11	**17**
1	1	2	0	1	0	0	**3**
1.05	0	0	0	0	0	0	**0**

Table 9.2: Distribution of Load Voltages across the Network with Wind Energy Input of 100MW in the Five Regions

Voltage Range	*No Wind*	*Lucea*	*Morant Point*	*Wigton*	*Rocky Point*	*Robins Bay*	*Dispersed Generation*
0.94	17	17	16	15	18	10	**0**
0.95	14	14	13	15	13	21	**15**
0.97	6	6	7	7	6	5	**11**
0.98	9	10	11	8	10	11	**21**
1	1	0	0	2	0	0	**0**
1.05	0	0	0	0	0	0	**0**

In comparison with the dispersed generation, it can be seen that the number of violations below the acceptable system voltage increased with the operation of voltage blocks in the regions. By the same token, overvoltage violations also resulted from this type of operation. From this information it is clear that the same positive impact is not realized when the EG is concentrated in a single area.

In chapter five it was established that the impact on generator buses was minimal. As such it was not deemed necessary to test those voltage levels under these scenarios.

Twenty Four Hour Operation

Using 0.94 as the reference voltage level, the number of times that voltages fell below this value is least when the wind energy is supplied via the Robins Bay wind farm site.

Table 9.3: Distribution of Load Voltages across the Network for 24 Hour Operation with Wind Energy Input of 50MW in the five Regions

Voltage Range	*No Wind*	*Lucea*	*Morant Point*	*Robins Bay*	*Rocky Point*	*Wigton*	*Dispersed Generation*
0.94	393	427	362	233	386	392	**163**
0.95	285	297	302	335	309	292	**206**
0.97	378	762	775	857	738	790	**372**
0.98	666	314	314	352	364	327	**957**
0.99	355	320	364	339	324	321	**405**
1.01	220	184	187	188	183	182	**201**
1.02	7	0	0	0	0	0	**0**

This is an indication that the greatest benefit is realised when concentrated injection is effected in this region. It is also of note that there is only a marginal improvement in bus voltages with the doubling of the generating capacity as illustrated in Table 9.4.

Table 9.4: Distribution of Load Voltages across the Network for 24 Hour Operation with Wind Energy Input of 100MW in the five Regions

Voltage Levels	*No Wind*	*Lucea*	*Morant Point*	*Wigton*	*Rocky Point*	*Robins Bay*	*Dispersed Generation*
0.94	393	461	349	381	385	226	**128**
0.95	285	295	307	269	324	339	**218**
0.97	378	744	744	819	755	864	**386**
0.98	666	308	338	340	348	357	**985**
0.99	355	313	377	312	312	332	**393**
1.01	220	183	189	183	180	186	**194**
1.02	7	0	0	0	0	0	**0**

Similar to the finding for the peak load analysis, the greatest benefit to bus voltage is realised when the EG is dispersed throughout the network.

Line Loading

The impact on the percentage line loading for injection of 100MW or 50MW at the sites considered was negligible as shown in the figures below.

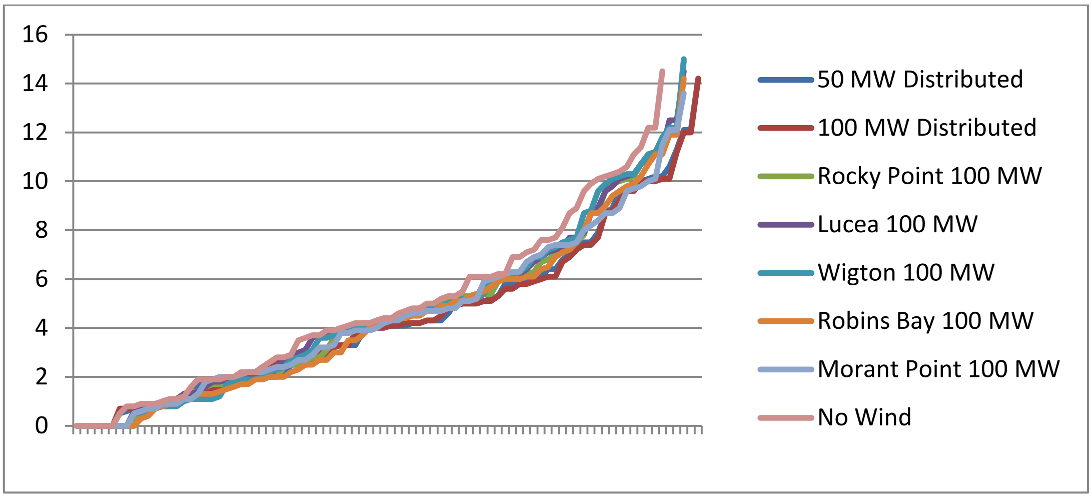

Figure 9.3: Comparison of Transformer Percentage Loading with Installed Wind Generation Evenly Distributed across the Network and in 100 MW Blocks

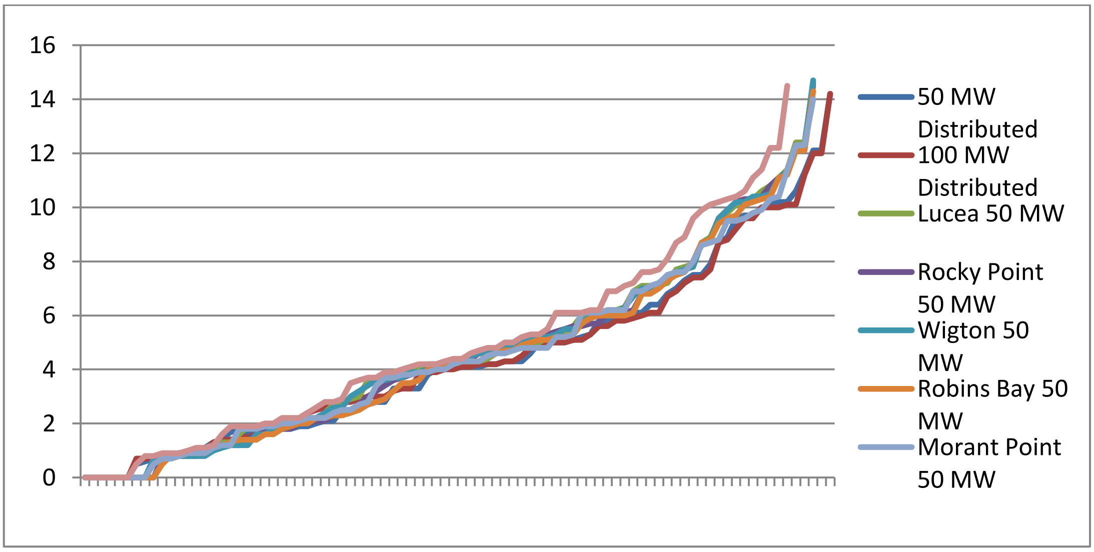

Figure 9.4: Comparison of Transformer Percentage Loading with Installed Wind Generation Evenly Distributed across the Network and in 100 MW Blocks

The relatively small percentage change is due, in part, to the fact that the capacity of the lines is very high relative to the power transmitted across the network. Notwithstanding however that the increases were small, there was an increase in the loading in the lines in close proximity to the wind farms; as expected.

Transformer Loading

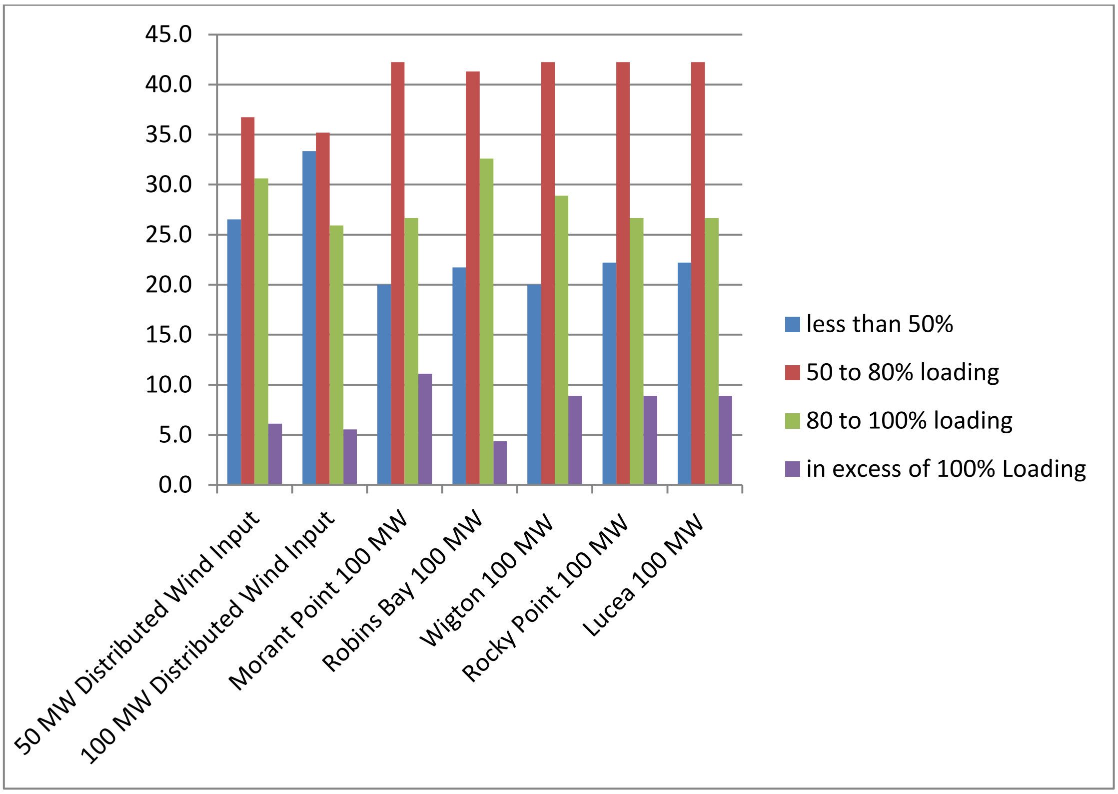

Figure 9.5: Comparison of Transformer Percentage Loading with Installed Wind Generation Distributed across the Network and in 100 MW Blocks

The vast majority of transformers operated with capacities of between fifty and eighty percent loading for all the scenarios highlighted by figures 6.5 and 6.6. It was clear that the greatest benefit to the network was realised when the systems were distributed across the network. The Robins Bay area had the greatest benefit from large injection of power. This is based on the fact that under both 100 MW and 50 MW scenarios, the smallest number of transformers was overloaded while correspondingly the largest number of units operated below 50% of capacity.

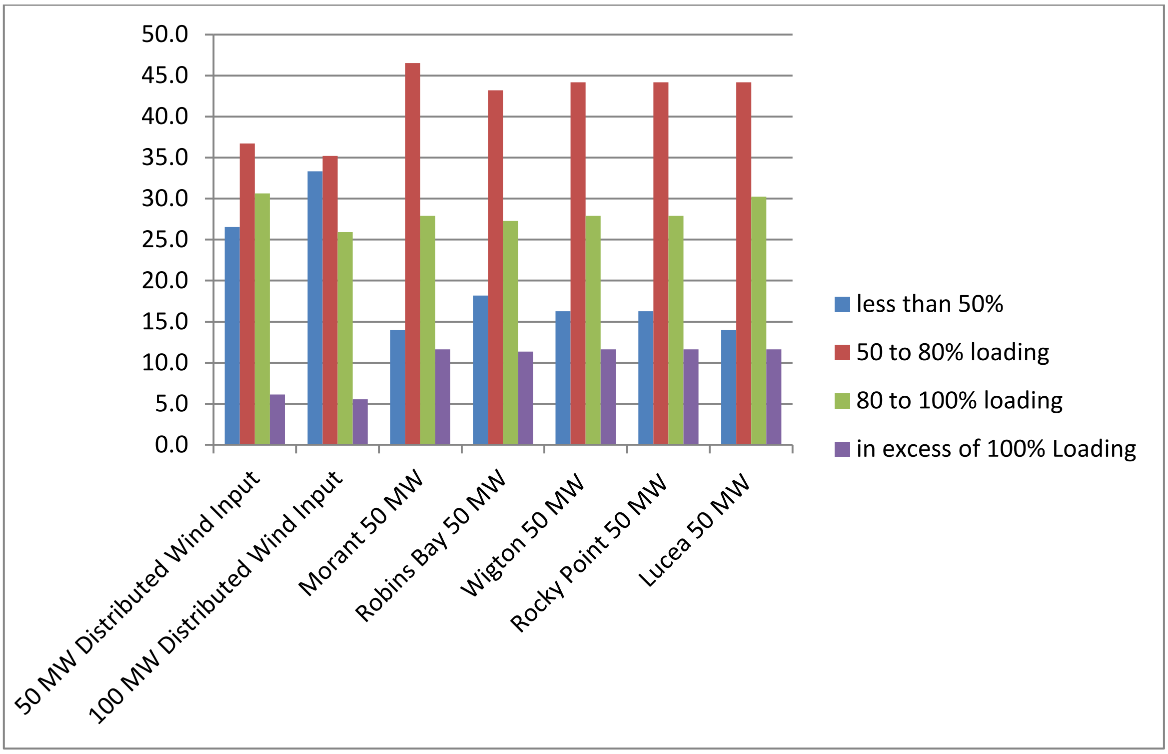

Figure 9.6: Comparison of Transformer Percentage Loading with Installed Wind Generation Distributed across the Network and in 50 MW Blocks

System Output and Losses

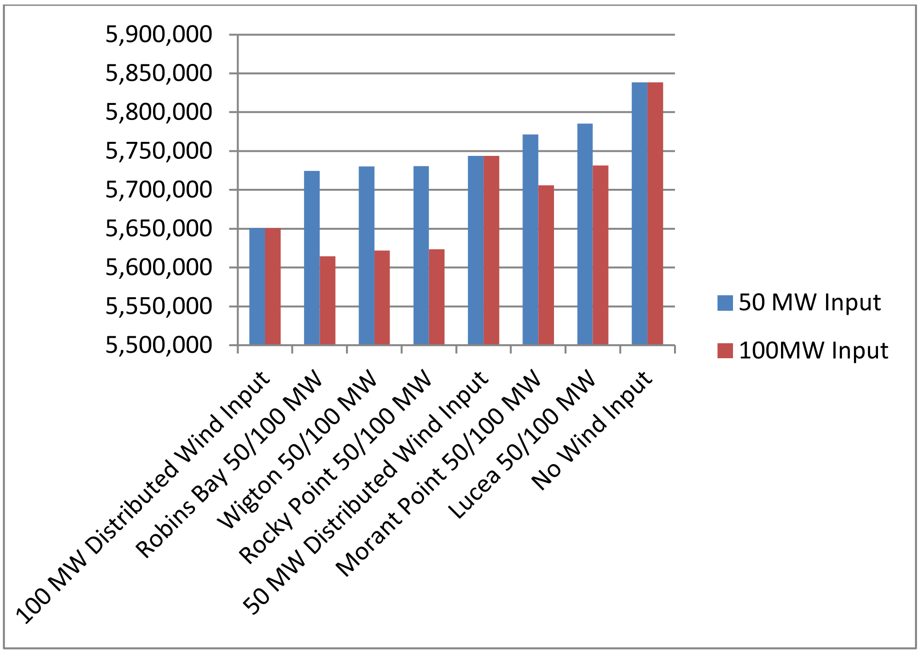

Figure 9.7: Energy Production from Fossil Fuel Sources for Installed Wind Generation Distributed across the Network and in 50 and 100 MW Blocks

Figures 6.7 to 6.9 highlight the fact that notwithstanding the doubling of capacity in the respective blocks, there was not a commensurate reduction in fossil fuel output.

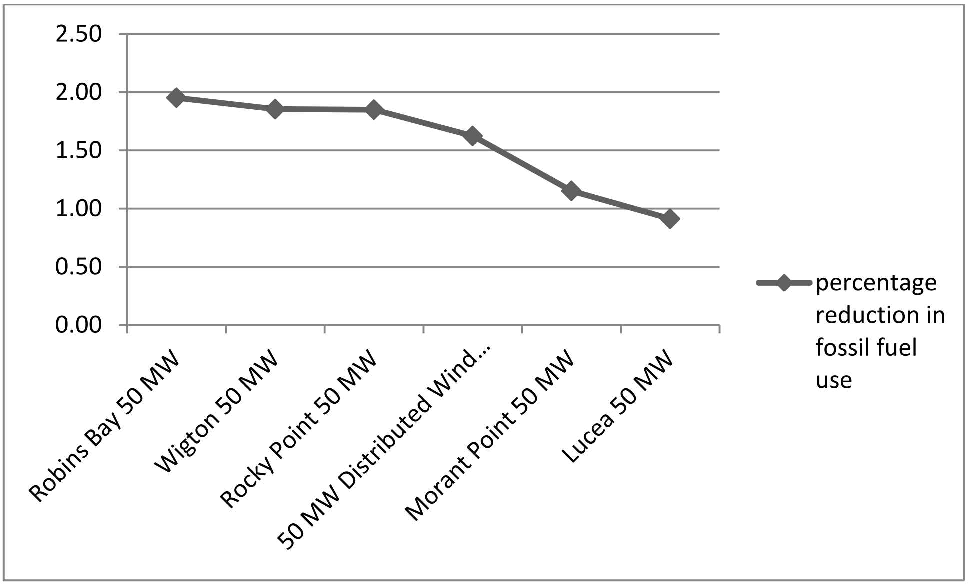

Figure 9.8: Percentage reductions in fossil fuel use from distributed and block installation of 50 MW wind Systems

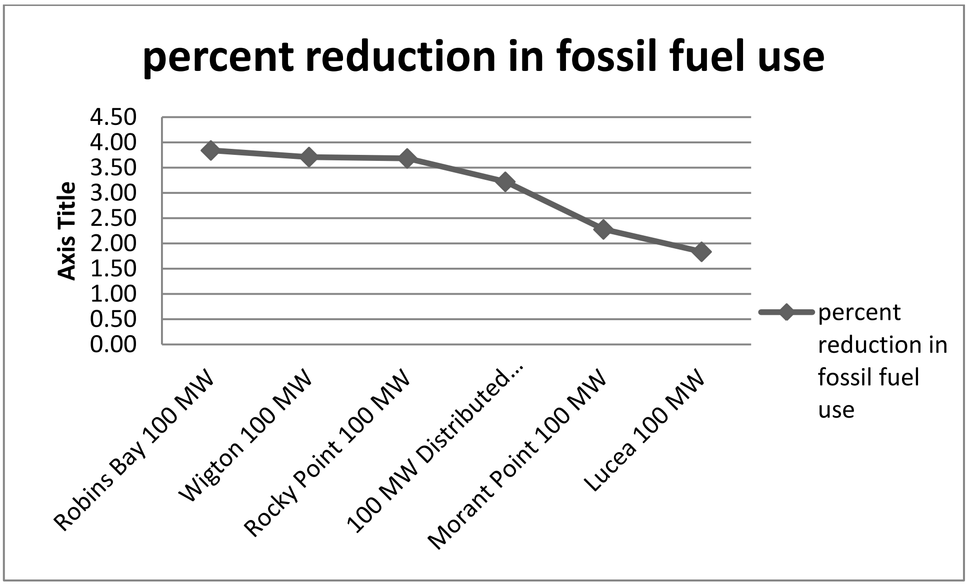

Figure 9.9: Percentage reductions in fossil fuel use from distributed and block installation of 100 MW wind Systems

Given that the impact of capacity is also linked to the wind regime, the effect of siting was also established based on the resultant losses produced in the system. This is illustrated in Table 9.5 below. Consistent with the reduction in fossil fuel output, input at the Robins Bay substation results in the best overall improvement in system operation. The overall benefit to the system's operation declines however as the input in the area is increased.

Table 9.5: Annual Transmission Losses Associated with Distributed and Blocks of 50 and 100 MW compared with System Operating without Wind

Location	Losses associated with 50 MW Input	Losses associated with 100 MW Input
Lucea	153,201	157,213
Rocky Point	148,431	149,458
Wigton	148,199	147,653
Morant Point	143,562	140,443
Distributed	142,682	138,486
Robins Bay	142,432	140,072
No Wind	148,705	148,705

As increased wind input is made to the system it can be seen as established in the table, that the greatest benefit is realized when distributed across the network. Although having better wind regimes for the central region of the island, it is clear that injection of generation in Morant Point is of benefit to network operation.

CHAPTER 10

Emission Results and Analysis for the Siting of Embedded Generators

Chapter ten provides the green house gasses emission results from the current use of fossil fuels. Additionally the chapter highlights the impact on these results with the use of renewable energy and based on the siting established in the previous chapter

Introduction

The emissions measured in metric tonnes per hour (Mt/h), as outlined in chapter six, is based on the sum of the carbon dioxide equivalent for each generating unit. The output of each unit is given at thirty minute intervals. The total daily CO_2 equivalent measured on this basis, for a gas turbine, GT3, is shown below:

Table 10.1: Carbon Dioxide Equivalent Emissions produced by Automotive Diesel Combustion Turbine in a Day at 30 Minute Intervals

Time of Day	Unit Output	CO2[eq.] (Mt/h)	Time of Day	Unit Output	CO2[eq.] (Mt/h)
12:00:00 AM	4.12	25.809	12:00:00 PM	10.97	36.462
12:30:00 AM	4.37	26.146	12:30:00 PM	10.9	36.338
01:00:00 AM	4.66	26.542	01:00:00 PM	10.85	36.250
01:30:00 AM	4.92	26.901	01:30:00 PM	10.79	36.144
02:00:00 AM	5.2	27.293	02:00:00 PM	10.74	36.056
02:30:00 AM	5.46	27.661	02:30:00 PM	10.7	35.986
03:00:00 AM	5.72	28.034	03:00:00 PM	10.63	35.864
03:30:00 AM	6	28.440	03:30:00 PM	10.67	35.934
04:00:00 AM	6.25	28.806	04:00:00 PM	10.72	36.021
04:30:00 AM	6.53	29.221	04:30:00 PM	10.77	36.109
05:00:00 AM	6.79	29.611	05:00:00 PM	10.84	36.232
05:30:00 AM	7.06	30.021	05:30:00 PM	10.88	36.303
06:00:00 AM	7.33	30.435	06:00:00 PM	10.93	36.391
06:30:00 AM	7.6	30.853	06:30:00 PM	10.99	36.497
07:00:00 AM	7.86	31.261	07:00:00 PM	10.99	36.497
07:30:00 AM	8.16	31.736	07:30:00 PM	10.73	36.039
08:00:00 AM	8.46	32.217	08:00:00 PM	10.48	35.602
08:30:00 AM	8.89	32.916	08:30:00 PM	10.22	35.152
09:00:00 AM	9.32	33.627	09:00:00 PM	9.98	34.740
09:30:00 AM	9.73	34.315	09:30:00 PM	9.72	34.298
10:00:00 AM	10.14	35.014	10:00:00 PM	9.45	33.844
10:30:00 AM	10.56	35.741	10:30:00 PM	9.21	33.444
11:00:00 AM	11.02	36.550	11:00:00 PM	8.97	33.047
11:30:00 AM	11.02	36.550	11:30:00 PM	8.75	32.687
Daily Total (Mt/h) = 793.82					

Based on the thirty minute output measurements the total emission is sum of the gas produced for the time interval. For this unit the total is therefore 793.82 Mt. The same unit produces on average outputs 8.897 MW over the same period. At this level of output the unit produces 32.93 Mt/h. Over the twenty four hour period the total production is 790.32 Mt of $CO_{2\ [equivalent]}$.

The percentage error using the average output is 0.441. On this basis, the average daily output of each unit as well as the load profile established in chapter 2, are used to determine the total annual GHG emissions.

GHG production is determined on the following bases:

1. The technology and fuel of the respective units
2. The years over which the research is based
3. The placement of the renewable energy sources
    a. Dispersed
    b. Concentrated in blocks
4. The magnitude of the renewable energy input

10.1 Technology and Fuel Consideration

Table 10.2: Carbon Dioxide Equivalent Emissions Produced without RES Input

Technology	2008	2010	2012	2015
ADO Combined Cycle	1707997	1717135	1764503	1817966
ADO Combustion Turbine	2713735	2981907	3105156	3384838
Medium Speed Turbine	3351407	3354903	3545970	3814443
Heavy Fuel Oil - Steam	11373998	12586737	14454470	17520362
Annual CO2 Equivalent Output (Mt)	**19149145**	**20642692**	**22872110**	**26539623**

Table 10.1 highlights the fact that the units responsible for the majority of GHG production are the steam units which utilizes heavy fuel oil. For periods considered the units produced in excess of fifty percent of the gasses produced[53].

The combined cycle units although having a consistently high output[54], produce the smallest level of GHG. This is in part attributable to the fact that the units are relatively new in comparison to the other automotive diesel oil units; therefore operating with greater level of efficiency.

The table below shows the percentage increase in green house gas production during the period considered and the corresponding average increase in generation output. The

[53] The high level of GHG production is consistent with the relative age of the units being used for electricity generation, as highlighted in chapter 2.
[54] Approximately 90% of capacity

information in the table further highlights the impact of the HFO units on GHG production. Notwithstanding that the units produce the highest output, the $CO_{2equivalent}$ production relative to the output of these units far outweigh that of all the other units combined. The fact that these generating units are used to service base load demand, further highlights their damaging effects[55].

Table 10.3: Comparison of GHG Production and Generator Output for the Generation Technologies used in the Network.

HFO Steam Units			
Percentage Increase in GHG Production	10.66	14.84	21.21
Average Percentage Increase in Output	5.20	5.54	8.22
	2.05	2.68	2.58
ADO Combined Cycle Units			
Percentage Increase in GHG Production	0.54	2.76	3.03
Average Percentage Increase in Output	0.86	4.42	4.79
	0.62	0.62	0.63
ADO Combustion Turbine			
Percentage Increase in GHG Production	9.882	4.13	9.01
Average Percentage Increase in Output	19.71	7.25	14.65
	0.50	0.57	0.61
Medium Speed Diesel			
Percentage Increase in GHG Production	0.104	5.70	7.57
Average Percentage Increase in Output	0.14	4.50	5.85
	0.77	1.27	1.29

[55] In recent times the old harbour number 4 unit have been cycled owing to its very low level of efficiency.

10.2: Impact of RES on GHG Production

As is expected, for a network consisting of thermal fossil fuel generating units, increases in MW output will also result in GHG production. Figure 10.1 illustrates the GHG production over the years considered when no without the additional renewable energy input.

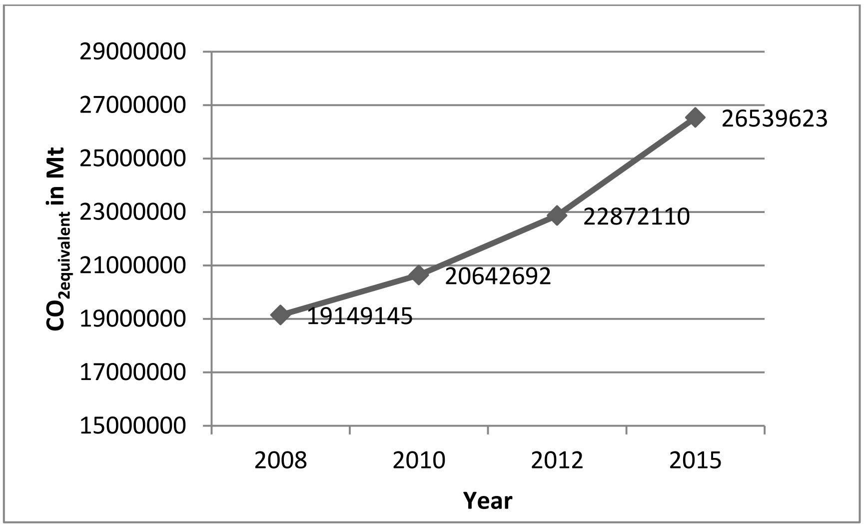

Figure 10.1: Annual Production of Carbon Dioxide Equivalent

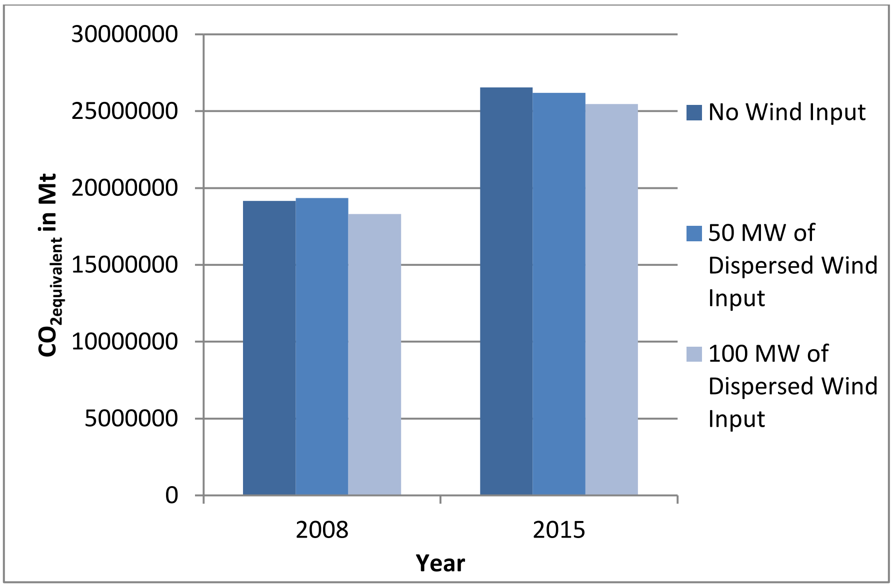

Figure 10.2: Carbon Dioxide Equivalent Production with and without Dispersed Generation in the years 2008 and 2015

As outlined in chapter 5, the wind generators were dispersed across the network in 10 and 20 MW blocks respectively. Given the five blocks under consideration, this represented a total of 50 and 100MW, respectively, distributed across the network. Figure 10.2 shows the impact of this dispersed generation on the overall impact of the GHG produced.

In contradiction to expectations, GHG production actually increased with the inclusion of the 10MW dispersed generation. A better perspective of the impact of the dispersed renewable input is highlighted in Table 10.4. an increased magnitude of renewable energy input dispersed across the network resulted in a significant reduction in GHG production.

Table 10.4: Percentage Reduction in GHG production with 10 and 20 MW Dispersed Generation for 2008 and 2015

Percent Reduction - 10MW Input	-1.04	1.35
Percent Reduction - 20MW Input	4.42	4.05

In considering the impact of location, the generators that were originally dispersed across the network were now concentrated into generation blocks in each of the five areas considered. The impact is shown in Figure 10.3 below.

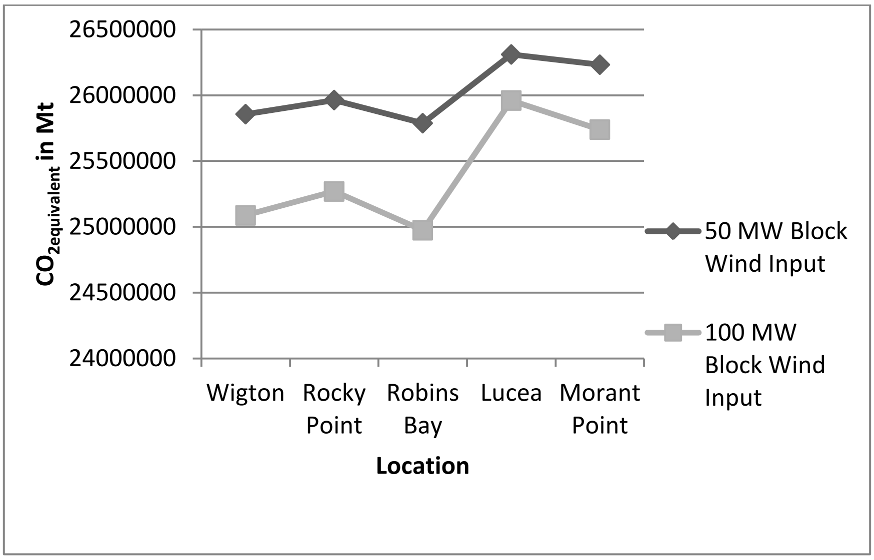

Figure 10.3: Carbon Dioxide Equivalent Production with 50 and 100MW Generation Blocks in the years 2008 and 2015

As expected there was a greater reduction n GHG production with increased wind input. The greatest reduction in both scenarios occurred with when used at the Robins Bay wind farm, while the least benefit was realised at the Lucea wind farm. When compared to the

GHG output without wind energy input the percentage reduction is highlighted in Figure 10.4.

The figure further highlights the minimal impact of the using the Lucea wind farm as a means of reducing GHG production. With only 50MW at the Robins Bay farm, the percentage reduction is greater than that at the Lucea facility. The impact as a result of locating the generating facility in Morant Point also showed very minimal effect when compared to Robins Bay. While the results at Lucea and Morant Point may have resulted from a poor wind regime, the fact that the capacity at the farms have doubled, shows marginal improvement further concretizes the fact that they have minimal positive effect in reducing the output of the fossil fuel units.

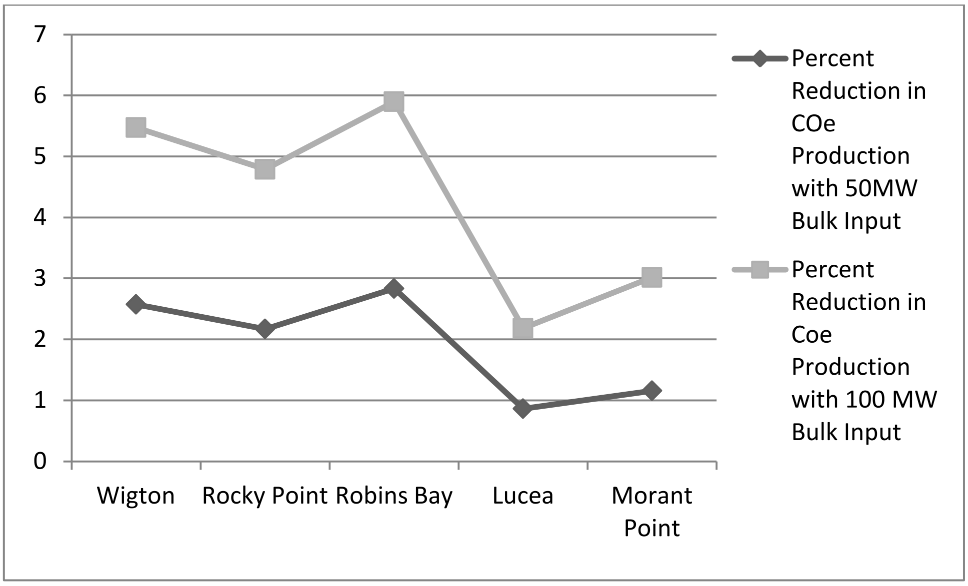

Figure 10.4: Percentage Reduction in GHG Production with Generating Blocks of 50 and 100MW in 2015.

CHAPTER 11

Conclusions & Further Work

This chapter concludes and reviews the findings of the research methodology applied. It also considers the limitation of the study by reviewing individual aspects of the research. The chapter also highlights the contributions of the key findings of the work. It concludes by considering aspects of this research that could be enhanced and expanded to provide greater impact on the Islands electricity supply

Use of renewable, embedded generation for electricity, assumes varying levels of importance depending on the jurisdiction in which it is applied. The delicate balance it is expected to provide for a country like Jamaica makes its implementation that more critical. At one end of the continuum the country requires expansion in its productive and manufacturing capacity, while at the other end it needs to maintain its image as a destination for clean air to facilitate its tourism industry.

Development of the Jamaican economy has stuttered over the years owing, in part, to the unavailability of a reliable, affordable source of electrical energy. The country has also suffered from the vagaries of making commitments, internationally and locally, without the benefit of critical review of its capacity to deliver on such commitments. The Kyoto Protocol and the establishment of the Millennial Goals[56] were watershed moments for our planet; which together helped to frame the local goals regarding the use of renewable energy. These targets having been set are not necessarily supported by the type of policy framework that will help in their attainment.

In meeting the objectives set out in chapter one, and herein repeated;

1. *Establish a robust computer model of the entire existing transmission network*

2. *Demonstrate the impact on the network resulting from increased annual load demands.*

3. *Demonstrate the impact of using wind, at previously identified sites, on the network*

4. *Establish the best siting of wind farms within the network from the sites identified*

5. *Establish the financial and environmental benefit of using renewable energy in the Jamaican network.*

6. *Provide the basis for the establishment of a policy framework for the use of embedded generation in the network.*

[56] Goal number7 on “Ensure Environmental Sustainability”

the research has focussed on the capability of the Jamaican power network's capacity to facilitate the inclusion of embedded generators up to and in excess of the targets set.

The technical considerations used in this assessment were:

1. Voltage Levels
2. Generation Cost
3. Fault Levels
4. System Loading/Losses
5. Contingencies

Additionally, the impact of the use of renewable sources on the production of green house gases was considered.

11.1 Research Limitations

These listed parameters were considered with the system operated as at 2008 generation and load levels with estimated growth for twelve years thereafter. Considerations were based on use of current generating facilities and the inclusion of renewable energy supply from wind.

Load

The load applied to each substation was based on the measured demand of the connected feeders to the location. Specific data for each load centre was therefore not available. The correctness of the data was predicated on the comparison of the calculated system data with overall system demand. Notwithstanding that was variation in the system demand based on time of year and day of the week, it was considered not significant enough to warrant an assessment based on these differences. As a result a single load profile was used to characterize the system demand.

Time related demand was based on the twenty four hour demand curve at thirty minute intervals. The demand curve was developed based on the feeder demand profile.

Generation

The actual despatch algorithm for the utility was unavailable. Reliance was therefore made on the fossil fuel generating facilities being operated on a must run basis. Load sharing among these units was based on optimal power flow. Load sharing at the individual busbars at the generating stations relied on participation factors which are based on the capacity of the units and the prescribed controlled bus voltage.

Cost considerations for the generators were based on their operations in 2007. Given that these costs would change with the increasing age of the units, it is difficult to rely on their veracity in proving a concrete measure of cost containment.

Wind Profiles

At the time of the development of this study the Island did not have the benefit of a wind map. Notwithstanding the development of such data, its availability remains limited for use by the developer and funding agency for the project. The wind data was therefore developed from weather stations in three regions of the country. Meteorological data, having been taken at a level lower than that used by wind turbines, were manipulated to reflect data at an acceptable turbine hub height.

11.2 Key Findings

Voltages

Satisfactory busbar voltages were used as an indication of the quality of supply. Based on the results of this study it was found that the use of embedded generators improved the quality of supply across the network. These are based on the results presented in sections 7.2.1, 8.1 & 9.1 and Table 7.12:

1. Load bus voltages declined with increases in system loading. This occurred both for daily load and total system load increases.

2. While individual generator bus voltages varied with changes in the system loading, the voltage at the controlled or substation buses remained relatively constant

3. Generator bus voltages were unaffected by the inclusion of embedded generators

4. Inclusion of embedded generators resulted in improvement in the load bus voltage levels for both peak and daily load operations

5. Voltage quality saw the greatest overall level of improvement when there was distribution of small embedded systems rather than large wind farms in the study areas.

Generation

Increased input from embedded generators resulted in a corresponding reduction in overall output from the fossil fuel units. This reduction in output is contextualised as:

1. Greater reduction of fossil fuel use resulted from increased input of embedded generators distributed across the network rather than in large blocks.
2. As referenced in section 9.5, the best overall reduction occurred when the generators are sited within the central region of the Island.
3. These benefits to the system were predicated on the use of generators that did not require reactive power form the existing network for operation.

Embedded Generation

A review of Table 7.4 shows that the average load factor of the installed generators across the network is 20%. Assuming this remains the same, the required installed capacity to meet the 20% wind based EG requirement in 2015 would be equal to the total existing installed capacity of fossil fuel and hydro.

System Loading

Transmission lines within the network operate at loading levels that are significantly below their capacities. As such no major construction or replacement of existing lines would be necessary in the foreseeable future.

At the current loading level, 72% of the transformers operate below eighty percent of capacity. Increasing the system loading by 20% resulted in 55% of the units being loaded up to the 80% margin. Simultaneously, the number of overloaded units and the extent to which they are overloaded increased significantly.

The inclusion of embedded generation did not result in any marked improvement in the loading profile of the network transformers. The small improvement realised occurred when the generation was distributed across the network. Notwithstanding however, improvement was also realized when bulk power was injected at the Robins Bay.

Based on these finding strengthening of the network through additional and or larger transformers will be necessary, regardless whether the EG is distributed or applied in blocks across the network.

System Losses

Increased system loading resulted in increased system losses. The trend was however reversed with the inclusion of embedded generators.

Reduction in system losses which continue to be a key objective of the utility company would be bolstered by the use of embedded generators within the network. While the use of EG caused a reduction in losses, doubling the output both distributed and bulk, did not produce commensurate gains to the system.

The use of embedded generators should therefore not be considered as a primary method for system loss reduction.

If however the inclusion of EG is to be used for this purpose, smaller systems distributed across the network will result in the greatest benefit as outlined in Table 9.5.

Fault Levels

Fault levels throughout the network increased marginally with increases in load demand. Fault levels were however significantly increased at substations connected directly to the wind farms.

It is therefore necessary for the following be considered when considering approval for the inclusion of EG

a. The utility company will be required to replace protective relaying equipment and switchgear, which may be a cost to EG generators or

b. EG suppliers will be required to effectively isolate/remove the wind farm from the affected substation in the event of a fault

Contingency Analysis

The Contingency Analysis showed that there was increased instability in the power network with increases in system loading. The Instability was demonstrated through the increased number of violations that resulted primarily from both the line and transformer contingencies[57]. The violations included low bus voltages as well as overloading of interbus transformers.

The inclusion of embedded generation caused a reduction in the number of violations for all the contingency studies conducted. This indicates that the use of embedded generating systems improved the stability of the network.

Green House Gas Production

Greenhouse gas production as was expected increase with increased system loads in the original system as the fossil fuel units increased their output to meet the new demand.

While increasing the amount of RES at the farms distributed across the network resulted in a reduction in GHG production; it was found that the greatest impact on GHG took place when bulk RES was injected at the Robins Bay wind farm.

11.3 Contribution of Key Findings

Given the findings highlighted in the previous section, the following conclusions can be made

1. The northern coast of the Island requires the generation input. This is based on the fact that

    a. There was a marked improvement on the overall voltage profile with the inclusion of embedded generation in this section of the network

    b. The reduction in overall system losses was greatest with additional generation in this area

2. Government policy regarding connection cost should focus on requiring deep connection cost given the increased fault levels that occurred in areas with added generation and the consequent requirement of the utility company to upgrade its facilities

[57] See section 5.2.5

3. Government policy geared towards supporting use of renewable energy generators should focus on the development of smaller systems spread across the Island. This is base on the fact that throughout the study it was shown that the greater overall impact on the network occurred when smaller generation was spread across the network.

4. Although Hydro systems were not specifically considered, given the distribution of rivers across the Island, support for the establishment of mini systems would aid in satisfying item #3.

5. The targets of Jamaica in relation to national and international renewable energy targets cannot be realised without having a negative impact on the national electricity grid unless additional firm capacity is established.

6. Having been able to conduct the analysis with the network to an acceptable level; it can now be used as the benchmark for expanded research work primarily within the local academic community but by overseas interests.

11.4 Further Work

Having completed this study and given some of the limitations identified, it is important that the following considerations be made in going forward.

Wind Data Expansion

It will be necessary to determine actual measured, electricity generating wind data at the various sites. This would allow for the accurate determination of the actual impact of each of the sites considered. Access to the current wind map would therefore be needed or the establishment of a buy in form the relevant stakeholders to provide measuring equipment.

Generation Data

Notwithstanding that a satisfactory method was used to determine generation output to meet prescribed load demands, the actual generation despatch algorithm would provide a more suitable all round result.

The use of up-to-date cost and operational data will make the measurement of GHG production, and other cost benefit analyses more plausible

Cost implications

Actual cost implications for every aspect of the work will be necessary. While trends have been established for the areas on which focus was placed, the actual cost associated with aspects such as loss reduction and EG expansion, is an important component to consider.

Additionally the implications of all the work necessary for the final cost to the consumer are also important. While from the engineering standpoint the changes are feasible, how it will affect the actual bottom line of the consumer, inclusive of manufacturer, householder etc is of critical importance.

Stability Studies

Notwithstanding the fact that stability studies were not conducted for this research, given the findings regarding the assessment through the contingency studies in chapter 7, it will be of importance to consider such effects going forward. These options are available in the programme selected for this study.

APPENDICES

Appendix A - Jamaican County Map

Appendix A shows the three broad areas into which the Island was divided for analysis. The division/classification is based on county boundaries. The appendix also includes the five areas identified by the authorities for possible wind input.

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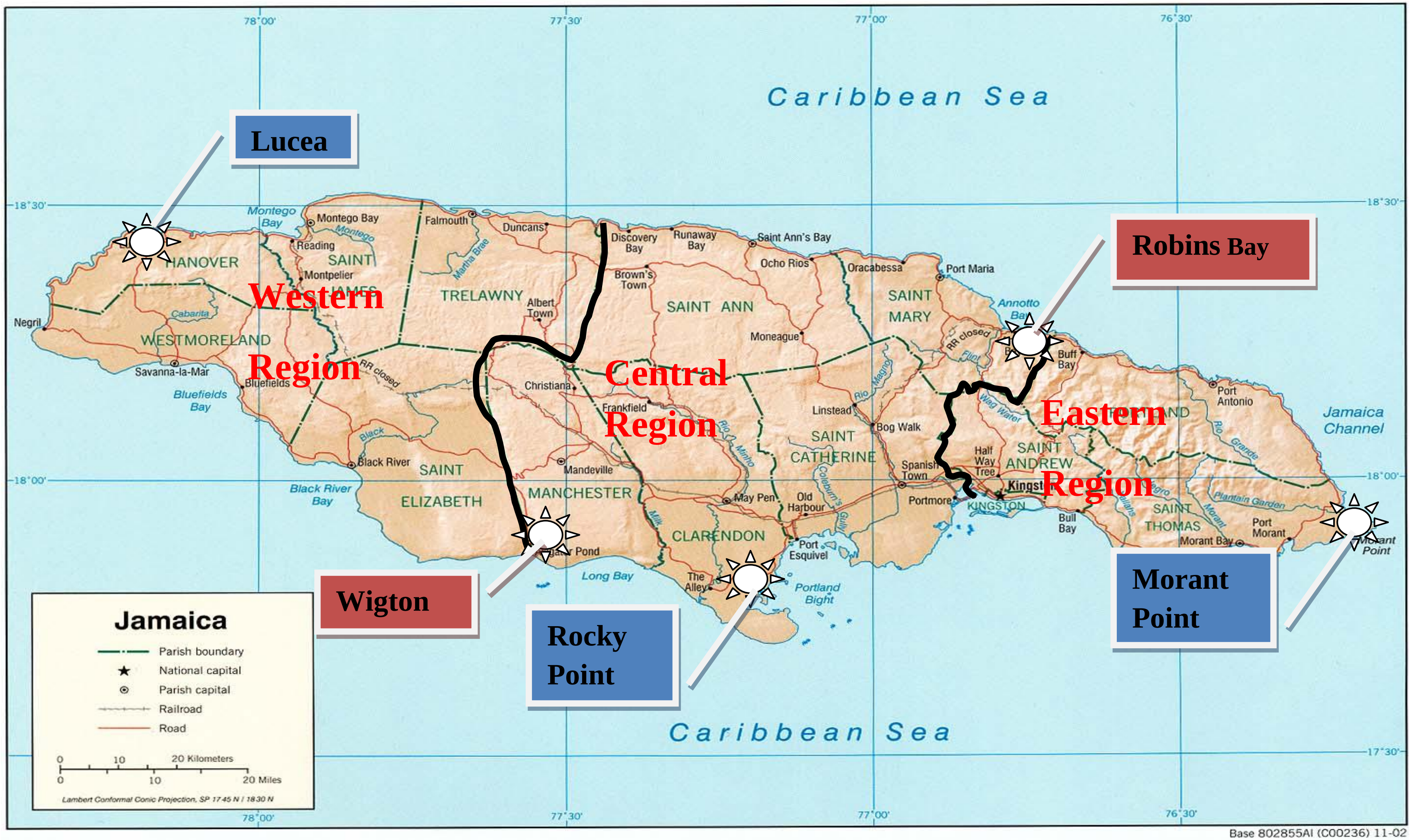

Caribbean Sea
Lucea
Robins Bay
Western
Region
Central
Region
Eastern
Region
Wigton
Rocky Point
Morant Point
Jamaica
Parish boundary
National capital
Parish capital
Railroad
Road
20 Kilometers
20 Miles
HANOVER
WESTMORELAND
SAINT JAMES
TRELAWNY
SAINT ANN
SAINT MARY
SAINT ELIZABETH
MANCHESTER
CLARENDON
SAINT CATHERINE
SAINT ANDREW
SAINT THOMAS
KINGSTON
Montego Bay
Falmouth
Duncans
Discovery Bay
Runaway Bay
Saint Ann's Bay
Ocho Rios
Oracabessa
Port Maria
Annotto Bay
Buff Bay
Port Antonio
Negril
Savanna-la-Mar
Bluefields Bay
Black River
Black River Bay
Mandeville
Christiana
Frankfield
May Pen
Old Harbour
Linstead
Bog Walk
Spanish Town
Portmore
Kingston
Bull Bay
Port Morant
Morant Bay
Morant Point
Long Bay
Portland Bight
Port Esquivel
Jamaica Channel
Base 802855AI (C00236) 11-02

Appendix B - System Data

Appendix B shows the system data used in creating the model. The data includes line, transformer, generator load and shunt information. The load data comprises that of the feeders supplied from the respective substations.

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Line Data

From Number	To Number	Resistance	Reactance	Susceptance	MVA Limit
82	15	0.0536	0.1208	0.0024	410
14	123	0.0161	0.0433	0.0009	410
30	14	0.0384	0.1069	0.002	410
26	14	0.1485	0.3275	0.0005	410
23	5	0.0287	0.0834	0.0214	520
3	4	0.042	0.1101	0.0014	410
102	81	0.0139	0.0313	0.0005	200
85	27	0.0393	0.0937	0.0016	410
27	56	0.0441	0.1	0.0019	410
76	126	0.0154	0.0309	0.0005	410
28	32	0.0137	0.0338	0.0006	410
28	84	0.0298	0.0716	0.0012	410
101	30	0.0235	0.0657	0.0005	410
94	89	0.0088	0.02	0.0003	410
94	95	0.0164	0.0311	0.0007	410
26	53	0.0229	0.0437	0.0013	410
8	86	0.1483	0.3264	0.005	410
100	25	0.0084	0.0162	0.0003	410
25	67	0.012	0.0334	0.0006	410
80	8	0.097	0.1174	0.0019	310
24	82	0.0414	0.0933	0.0018	410
56	24	0.0313	0.0708	0.0014	410
80	8	0.097	0.1174	0.0019	310
94	4	0.0503	0.1145	0.0023	410
2	93	0.0279	0.0812	0.0208	520
77	1	0.1487	0.3361	0.0058	410

From Number	To Number	Resistance	Reactance	Susceptance	MVA Limit
47	23	0.0339	0.0988	0.0253	410
61	75	0.0125	0.0372	0.0097	520
8	74	0.097	0.3445	0.0062	410
22	124	0.0143	0.0323	0.0006	410
60	83	0.0269	0.0609	0.0001	410
22	99	0.0225	0.0447	0.0008	410
90	4	0.0445	0.0874	0.0017	410
95	22	0.0321	0.0613	0.0012	410
58	94	0.059	0.1103	0.0023	410
90	58	0.0094	0.0185	0.0004	410
22	78	0.0374	0.0844	0.0016	410
76	57	0.0512	0.0622	0.001	310
76	59	0.0731	0.146	0.0026	410
59	100	0.0615	0.1393	0.0027	410
55	88	0.0229	0.0517	0.0013	410
22	32	0.0336	0.0496	0.0014	410
54	88	0.113	0.2556	0.005	410
86	54	0.1941	0.4274	0.0072	410
21	93	0.0117	0.2194	0.0219	410
29	4	0.046	0.1153	0.002	410
61	75	0.0125	0.0372	0.0097	520
61	93	0.0118	0.0587	0.0366	720
23	2	0.0365	0.1061	0.0272	520
49	97	0.0107	0.0242	0.0005	410
60	49	0.0179	0.0401	0.0008	410
67	102	0.0105	0.0292	0.0005	410
74	86	0.0775	0.2705	0.0048	410
61	21	0.0132	0.0705	0.0494	720

From Number	To Number	Resistance	Reactance	Susceptance	MVA Limit
75	87	0.0133	0.4255	0.0412	720
92	76	0.0926	0.1367	0.0023	410
55	48	0.0368	0.083	0.0016	410
88	79	0.0706	0.1594	0.0029	410
79	92	0.038	0.0859	0.0011	410
80	85	0.0315	0.0712	0.0014	410
47	87	0.0067	0.0211	0.0021	720
75	47	0.0222	0.0706	0.017	520
96	84	0.012	0.0401	0.0007	410
125	46	0.0109	0.025	0.0005	410
97	3	0.0176	0.0346	0.0007	410
102	46	0.0126	0.0247	0	410
46	89	0.1346	0.1777	0.0022	410
84	123	0.0067	0.0179	0.0003	410
20	22	0.0286	0.071	0.0015	410
124	32	0.0153	0.0347	0.0007	410
99	91	0.0158	0.0353	0.0007	410
91	32	0.0132	0.03	0.0004	520
32	84	0.017	0.0492	0.0013	410
15	83	0.0697	0.1577	0.0031	410
101	96	0.0139	0.041	0.0007	410
73	3	0.097	0.1174	0.0019	310
99	101	0.0101	0.0281	0.0008	410
1	73	0.0771	0.1857	0.0029	410
1	29	0.0496	0.1046	0.0019	410

Transformer Data

From Number	To Number	Resistance	Reactance	Transformer Configuration	Phase (Deg)	MVA Limit
21	22	0.0043	0.1499	GWye - Delta	-30	80
23	24	0.0125	0.2884	GWye - Delta	-30	30
67	71	0.0096	0.2598	GWye - Delta	-30	37.5
84	107	0.0076	0.2043	GWye - Delta	-30	62.5
16	54	0.0479	0.7665	Wye - Delta	-30	10
61	119	0.0076	0.2437	GWye - Delta	-30	55
87	88	0.0062	0.1977	GWye - Delta	-30	120
75	76	0.0063	0.2001	GWye - Delta	-30	60
61	72	0.0039	0.1467	GWye - Delta	-30	80
21	22	0.0062	0.1981	GWye - Delta	-30	60
2	3	0.0109	0.2948	GWye - Delta	-30	30
32	45	0.0157	0.3611	Wye - Delta	-30	28.5
21	22	0.0043	0.1508	GWye - Delta	-30	80
83	127	0.1491	1.7894	Wye - Delta	0	5
97	98	0.1329	1.5945	Delta - Delta	0	4.5
32	31	0.0078	0.2502	GWye - Delta	-30	32
84	105	0.017	0.3748	GWye - Delta	-30	25
5	8	0.0043	0.1487	GWye - Delta	-30	80
61	69	0.0039	0.1475	GWye - Delta	-30	80
8	41	0.0037	0.1183	GWye - Delta	-30	60
8	40	0.004	0.1279	GWye - Delta	-30	60
49	50	0.1329	1.5945	Delta - Delta	0	4.5
93	94	0.0197	0.4529	GWye - Delta	-30	22
82	19	0.2021	2.4249	Wye - Delta	-30	3
32	39	0.0157	0.3611	Wye - Delta	-30	28.5
32	38	0.0046	0.1482	GWye - Delta	-30	80

From Number	To Number	Resistance	Reactance	Transformer Configuration	Phase (Deg)	MVA Limit
71	46	0.0037	3.6646	GWye - Delta	-30	22
8	9	0.0179	0.4119	Wye - Delta	-30	28.5
47	48	0.0062	0.1982	GWye - Delta	-30	80
84	104	0.017	0.3748	GWye - Delta	-30	25
8	10	0.015	0.3153	GWye - Delta	-30	20
126	121	0.0005	0.5273	Wye - Wye	0	22
8	11	0.022	0.4622	GWye - Delta	-30	25
93	94	0.012	0.4561	GWye - Delta	-30	100
8	12	0.0186	0.391	GWye - Delta	-30	20
84	106	0.0076	0.2043	GWye - Delta	-30	62.5
8	13	0.0186	0.391	GWye - Delta	-30	20
8	122	0.0119	0.2368	GWye - Delta	-30	40
61	118	0.0076	0.2437	GWye - Delta	-30	55
61	70	0.0043	0.1364	GWye - Delta	-30	87.4
8	43	0.0048	0.1529	GWye - Delta	-30	60
61	67	0.0105	0.2829	GWye - Delta	-30	37.5

Load Data

Bus Number	Zone Number of Bus	MW	MVar	Power Factor	MVA
1	1	5.78	3.05	0.88	6.53
4	1	1.6	0.15	1	1.61
8	1	34.28	8.12	0.97	35.22
14	2	11.27	3.36	0.96	11.76
15	1	19.97	1.85	1	20.05
20	2	37.31	11.01	0.96	38.9
22	2	5.62	4.29	0.79	7.07
24	4	6.21	2.48	0.93	6.69
25	1	6.95	5.18	0.8	8.67
26	2	11.04	3.22	0.96	11.5
27	4	3.22	1.31	0.93	3.47
28	2	18.93	0.09	1	18.93
29	1	6.8	1.6	0.97	6.98
30	2	29.43	20.56	0.82	35.9
33	2	55.12	2.93	1	55.2
48	1	8.05	2.77	0.95	8.51
53	2	3.68	2.77	0.8	4.6
54	1	12.74	2.77	0.98	13.03
56	1	4.42	1.82	0.92	4.78
57	4	11.79	5.84	0.9	13.16
58	1	19.04	4.81	0.97	19.64
59	1	8.53	4.72	0.88	9.75
60	1	16.1	8.25	0.89	18.09
73	1	7.07	2.68	0.94	7.56
74	1	26.97	11.18	0.92	29.2
76	1	19.38	6.12	0.95	20.32
77	1	8.97	4.69	0.89	10.12

Bus Number	Zone Number of Bus	MW	MVar	Power Factor	MVA
78	2	22.78	9.97	0.92	24.86
79	1	12.95	3.85	0.96	13.51
80	1	30.46	10.54	0.94	32.24
81	1	16.4	5.95	0.94	17.44
83	1	12.88	5.09	0.93	13.85
84	2	7.29	2.59	0.94	7.74
85	1	11.27	2.51	0.98	11.55
86	1	23.28	0.99	1	23.3
88	1	18.2	7.68	0.92	19.75
89	1	4.73	2.96	0.85	5.58
91	2	26.88	0	1	26.88
94	4	15.33	5.4	0.94	16.26
95	1	31.71	13.03	0.92	34.28
96	2	22.56	2.16	1	22.66
97	4	3.93	1.42	0.94	4.18
99	2	38.87	2.44	1	38.95
100	1	9.02	5.62	0.85	10.63
101	2	20.38	0	1	20.38
102	1	5.03	3.11	0.85	5.91
123	2	2.9	1.87	0.84	3.45
124	2	2.9	1.88	0.84	3.45

Generator Data on Peak 2015 Load

Bus Number	Zone Number of Bus	MVA	Generator Output MW	Maximum Output MW	Generator Output MVar	Maximum Output MVar	MW Limits Enforcement	Participation Factor	Automatic Gain Control	Automatic Voltage Regulation	Internal Resistance	Internal Reactance
38	1	62.82	62.74	65.1	3.15	42	YES	6.51	YES	YES	0	0.13
70	4	68.93	62.06	65.1	30	60	YES	6.51	YES	NO	0	0.13
69	1	68.23	61.28	63.5	30	42	YES	6.35	YES	NO	0	0.13
72	1	63.93	56.46	58.5	30	45	YES	5.85	YES	NO	0	0.13
40	1	41.56	41.5	43	2.33	26.65	YES	4.3	YES	YES	0.07	0.07
41	1	41.56	41.5	43	2.33	26.65	YES	4.3	YES	YES	0.07	0.07
43	1	41.56	41.5	43	2.33	26.65	YES	4.3	YES	YES	0.07	0.07
71	1	37.01	36.67	38	5	16	YES	3.8	YES	NO	0	1
118	1	36.69	35.78	37.08	8.09	30	YES	3.71	YES	YES	0	1
119	1	33.71	32.73	33.91	8.09	30	YES	3.39	YES	YES	0	1
107	2	34.52	29.53	30.6	17.88	22.5	YES	3.06	YES	YES	0	0.13
106	2	33.54	29.53	30.6	15.9	20	YES	3.06	YES	YES	0	0.13

Bus Number	Zone Number of Bus	MVA	Generator Output MW	Maximum Output MW	Generator Output MVar	Maximum Output MVar	MW Limits Enforcement	Participation Factor	Automatic Gain Control	Automatic Voltage Regulation	Internal Resistance	Internal Reactance
31	1	32.89	25.32	32	21	21	YES	3.2	YES	YES	0	0.13
11	4	23.57	23.52	25	1.48	16.89	YES	2.5	YES	YES	0	0.13
122	1	20.77	20.61	25	2.59	29.61	YES	2.5	YES	YES	0	1
105	2	22.69	19.3	20	11.92	15	YES	2	YES	YES	0	0.13
104	2	22.69	19.3	20	11.92	15	YES	2	YES	YES	0	0.13
9	2	17.49	17.45	22.74	1.21	13.8	YES	2.27	YES	YES	0	0.13
45	1	29.61	16.64	21.5	24.5	24.5	YES	2.15	YES	YES	0	0.13
39	1	21.74	16.64	21.5	14	14	YES	2.15	YES	YES	0	0.13
12	4	17.02	15.52	20	7	80	YES	2	YES	YES	0	0.13
13	4	14.87	14.81	19.87	1.22	14	YES	1.99	YES	YES	0	0.13
10	4	16.38	14.81	19.87	7	80	YES	1.99	YES	YES	0	0.13
121	1	8.2	6.51	10	5	5	YES	10	YES	NO	0	1
16	1	7.41	5.93	6	4.45	4.5	YES	10	NO	NO	0.01	0.1
50	1	4.61	4.5	4.52	1	1	YES	10	NO	NO	0.01	0.1
127	1	5	4	4.05	3	3	YES	10	NO	NO	0	1

Bus Number	Zone Number of Bus	MVA	Generator Output MW	Maximum Output MW	Generator Output MVar	Maximum Output MVar	MW Limits Enforcement	Participation Factor	Automatic Gain Control	Automatic Voltage Regulation	Internal Resistance	Internal Reactance
98	4	4.24	3.39	3.39	2.54	2.54	YES	10	NO	NO	0.01	0.1
19	1	2.94	2.35	2.49	1.76	1.76	YES	10	NO	NO	0.01	0.1

Switched Shunt Data on Peak 2015 Load

Number of Bus	Regulated Bus Num	Status	Control Mode	Actual MVar	Per Unit Regulated Volt	Deviation	Nominal MVar	Max MVar
8	8	Closed	Continuous	12	1	0	12	12
14	14	Closed	Continuous	2.88	0.9804	-0.0096	3	3
15	15	Closed	Continuous	4.77	0.9234	-0.0666	5.6	5.6
32	32	Closed	Continuous	3.97	0.9968	0	4	4
55	55	Open	Continuous	0	0.9625	-0.0275	0	12
74	74	Closed	Continuous	4.55	0.9538	-0.0362	5	5
77	77	Closed	Continuous	8.59	0.9267	-0.0633	10	10
79	79	Open	Continuous	0	0.9526	-0.0374	8.36	10
80	80	Closed	Continuous	4.61	0.9604	-0.0296	5	5
86	86	Closed	Continuous	4.43	0.9608	-0.0292	4.8	4.8
88	88	Open	Continuous	0	0.9596	-0.0304	10.62	24

Appendix C - Output Data Samples

Appendix C shows samples of raw output data used throughout this study. The information includes generation output with and without embedded generation based on capacity and siting; bus voltage information; contingency and fault data based on capacity as well as emissions data based on capacity and siting.

Output of fossil fuel units and the corresponding system losses for Jamaica's transmission network without the inclusion of EG.

Generation and Loss Data for 2008						
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Reserve**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	NO	386.48	432.84	5.2	193.24	2.6
12:30:00 AM	NO	395.43	423.89	5.35	197.715	2.675
01:00:00 AM	NO	405.53	413.79	5.55	202.765	2.775
01:30:00 AM	NO	414.76	404.56	5.74	207.38	2.87
02:00:00 AM	NO	424.64	394.68	5.97	212.32	2.985
02:30:00 AM	NO	434.19	385.13	6.22	217.095	3.11
03:00:00 AM	NO	443.23	376.09	6.46	221.615	3.23
03:30:00 AM	NO	453.15	366.17	6.74	226.575	3.37
04:00:00 AM	NO	462.4	356.92	7.05	231.2	3.525
04:30:00 AM	NO	472.27	347.05	7.39	236.135	3.695
05:00:00 AM	NO	481.51	337.81	7.72	240.755	3.86
05:30:00 AM	NO	491.45	327.87	8.11	245.725	4.055
06:00:00 AM	NO	501.01	318.31	8.52	250.505	4.26
06:30:00 AM	NO	510.87	308.45	8.97	255.435	4.485
07:00:00 AM	NO	520.25	299.07	9.43	260.125	4.715
07:30:00 AM	NO	531.3	288.02	9.99	265.65	4.995
08:00:00 AM	NO	542.52	276.8	10.7	271.26	5.35
08:30:00 AM	NO	558.14	261.18	11.61	279.07	5.805
09:00:00 AM	NO	573.65	245.67	12.42	286.825	6.21
09:30:00 AM	NO	588.89	230.43	13.28	294.445	6.64
10:00:00 AM	NO	603.6	215.72	14.14	301.8	7.07
10:30:00 AM	NO	619.03	200.29	15.1	309.515	7.55
11:00:00 AM	NO	635.77	183.55	16.14	317.885	8.07
11:30:00 AM	NO	634.19	185.13	16.12	317.095	8.06
12:00:00 PM	NO	632.37	186.95	15.98	316.185	7.99

Generation and Loss Data for 2008						
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Reserve**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:30:00 PM	NO	629.78	189.54	15.8	314.89	7.9
01:00:00 PM	NO	627.97	191.35	15.68	313.985	7.84
01:30:00 PM	NO	625.66	193.66	15.55	312.83	7.775
02:00:00 PM	NO	623.83	195.49	15.41	311.915	7.705
02:30:00 PM	NO	622.27	197.05	15.29	311.135	7.645
03:00:00 PM	NO	619.56	199.76	15.11	309.78	7.555
03:30:00 PM	NO	621.42	197.9	14.92	310.71	7.46
04:00:00 PM	NO	623.06	196.26	14.75	311.53	7.375
04:30:00 PM	NO	624.95	194.37	14.59	312.475	7.295
05:00:00 PM	NO	627.78	191.54	14.52	313.89	7.26
05:30:00 PM	NO	629.23	190.09	14.41	314.615	7.205
06:00:00 PM	NO	630.98	188.34	14.34	315.49	7.17
06:30:00 PM	NO	632.27	187.05	14.31	316.135	7.155
07:00:00 PM	NO	634.19	185.13	14.21	317.095	7.105
07:30:00 PM	NO	624.82	194.5	13.63	312.41	6.815
08:00:00 PM	NO	615.47	203.85	13.09	307.735	6.545
08:30:00 PM	NO	606.15	213.17	12.58	303.075	6.29
09:00:00 PM	NO	597.22	222.1	12.09	298.61	6.045
09:30:00 PM	NO	587.8	231.52	11.6	293.9	5.8
10:00:00 PM	NO	577.91	241.41	11.11	288.955	5.555
10:30:00 PM	NO	569.2	250.12	10.72	284.6	5.36
11:00:00 PM	NO	560.88	258.44	10.37	280.44	5.185
11:30:00 PM	NO	552.87	266.45	10.04	276.435	5.02
Per Day					13390.95	277.01
Per Annum					4887696.75	101108.7

Generation and Loss Data for 2015					
Simulation Time	**Total Generator Output (MW)**	**Reserve**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	460.53	358.79	7.26	230.265	3.63
12:30:00 AM	471.2	348.12	7.49	235.6	3.745
01:00:00 AM	483.27	336.05	7.8	241.635	3.9
01:30:00 AM	494.37	324.95	8.16	247.185	4.08
02:00:00 AM	506.25	313.07	8.58	253.125	4.29
02:30:00 AM	517.75	301.57	9.05	258.875	4.525
03:00:00 AM	528.71	290.61	9.51	264.355	4.755
03:30:00 AM	540.65	278.67	9.98	270.325	4.99
04:00:00 AM	551.74	267.58	10.49	275.87	5.245
04:30:00 AM	563.64	255.68	11.05	281.82	5.525
05:00:00 AM	574.8	244.52	11.59	287.4	5.795
05:30:00 AM	586.75	232.57	12.22	293.375	6.11
06:00:00 AM	598.28	221.04	12.85	299.14	6.425
06:30:00 AM	610.18	209.14	13.56	305.09	6.78
07:00:00 AM	621.47	197.85	14.25	310.735	7.125
07:30:00 AM	634.77	184.55	15.08	317.385	7.54
08:00:00 AM	648.21	171.11	16.02	324.105	8.01
08:30:00 AM	666.78	152.54	17.13	333.39	8.565
09:00:00 AM	685.43	133.89	18.29	342.715	9.145
09:30:00 AM	703.68	115.64	19.44	351.84	9.72
10:00:00 AM	721.29	98.03	20.58	360.645	10.29
10:30:00 AM	739.76	79.56	21.82	369.88	10.91
11:00:00 AM	759.74	59.58	23.55	379.87	11.775
11:30:00 AM	758.07	61.25	23.36	379.035	11.68
12:00:00 PM	755.88	63.44	23.17	377.94	11.585
12:30:00 PM	752.74	66.58	22.9	376.37	11.45
01:00:00 PM	750.57	68.75	22.74	375.285	11.37
01:30:00 PM	747.8	71.52	22.54	373.9	11.27
02:00:00 PM	745.59	73.73	22.35	372.795	11.175
02:30:00 PM	743.71	75.61	22.18	371.855	11.09

Generation and Loss Data for 2015					
Simulation Time	**Total Generator Output (MW)**	**Reserve**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
03:00:00 PM	740.46	78.86	21.94	370.23	10.97
03:30:00 PM	742.7	76.62	21.75	371.35	10.875
04:00:00 PM	744.7	74.62	21.59	372.35	10.795
04:30:00 PM	746.98	72.34	21.45	373.49	10.725
05:00:00 PM	750.4	68.92	21.39	375.2	10.695
05:30:00 PM	752.09	67.23	21.25	376.045	10.625
06:00:00 PM	754.17	65.15	21.17	377.085	10.585
06:30:00 PM	755.63	63.69	21.06	377.815	10.53
07:00:00 PM	758.11	61.21	21.1	379.055	10.55
07:30:00 PM	746.81	72.51	20.29	373.405	10.145
08:00:00 PM	735.56	83.76	19.5	367.78	9.75
08:30:00 PM	724.35	94.97	18.77	362.175	9.385
09:00:00 PM	713.62	105.7	18.07	356.81	9.035
09:30:00 PM	702.28	117.04	17.34	351.14	8.67
10:00:00 PM	690.38	128.94	16.62	345.19	8.31
10:30:00 PM	679.9	139.42	16.04	339.95	8.02
11:00:00 PM	669.92	149.4	15.51	334.96	7.755
11:30:00 PM	660.22	159.1	14.99	330.11	7.495
Daily				**15996**	**407**
Annual				**5838520**	**148705**

Output of fossil fuel units and the corresponding system losses for Jamaica's transmission network with the inclusion of 100 MW of dispersed EG

Generation and Loss Data in 2008 With 100 MW Wind					
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	NO	375.84	4.91	187.92	2.455
12:30:00 AM	NO	384.73	5.04	192.365	2.52
01:00:00 AM	NO	394.8	5.23	197.4	2.615
01:30:00 AM	NO	404.67	5.42	202.335	2.71
02:00:00 AM	NO	414.49	5.64	207.245	2.82
02:30:00 AM	NO	424.05	5.87	212.025	2.935
03:00:00 AM	NO	433.08	6.1	216.54	3.05
03:30:00 AM	NO	441.58	6.37	220.79	3.185
04:00:00 AM	NO	450.87	6.71	225.435	3.355
04:30:00 AM	NO	460.8	7.1	230.4	3.55
05:00:00 AM	NO	470.1	7.47	235.05	3.735
05:30:00 AM	NO	477.06	7.8	238.53	3.9
06:00:00 AM	NO	486.49	8.2	243.245	4.1
06:30:00 AM	NO	495.12	8.62	247.56	4.31
07:00:00 AM	NO	504.46	9.05	252.23	4.525
07:30:00 AM	NO	514.9	9.57	257.45	4.785
08:00:00 AM	NO	525.97	10.15	262.985	5.075
08:30:00 AM	NO	542.48	10.94	271.24	5.47
09:00:00 AM	NO	557.93	11.73	278.965	5.865
09:30:00 AM	NO	549.18	12.14	274.59	6.07
10:00:00 AM	NO	563.85	12.99	281.925	6.495
10:30:00 AM	NO	578.02	13.9	289.01	6.95
11:00:00 AM	NO	594.22	14.41	297.11	7.205
11:30:00 AM	NO	593.21	14.36	296.605	7.18
12:00:00 PM	NO	591.37	14.22	295.685	7.11

Generation and Loss Data in 2008 With 100 MW Wind					
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:30:00 PM	NO	580.65	13.74	290.325	6.87
01:00:00 PM	NO	578.89	13.62	289.445	6.81
01:30:00 PM	NO	576	13.49	288	6.745
02:00:00 PM	NO	574.15	13.35	287.075	6.675
02:30:00 PM	NO	573.8	13.27	286.9	6.635
03:00:00 PM	NO	570.19	13.11	285.095	6.555
03:30:00 PM	NO	575.95	12.96	287.975	6.48
04:00:00 PM	NO	577.5	12.79	288.75	6.395
04:30:00 PM	NO	580.43	12.85	290.215	6.425
05:00:00 PM	NO	583.21	12.74	291.605	6.37
05:30:00 PM	NO	602.29	13.06	301.145	6.53
06:00:00 PM	NO	604.2	12.99	302.1	6.495
06:30:00 PM	NO	613.38	13.12	306.69	6.56
07:00:00 PM	NO	615.52	13.14	307.76	6.57
07:30:00 PM	NO	604.95	12.56	302.475	6.28
08:00:00 PM	NO	595.65	12.06	297.825	6.03
08:30:00 PM	NO	586.99	11.61	293.495	5.805
09:00:00 PM	NO	578.1	11.17	289.05	5.585
09:30:00 PM	NO	569.76	10.83	284.88	5.415
10:00:00 PM	NO	559.97	10.37	279.985	5.185
10:30:00 PM	NO	552.15	10.03	276.075	5.015
11:00:00 PM	NO	543.82	9.69	271.91	4.845
11:30:00 PM	NO	541.13	9.51	270.565	4.755
Daily				**12783.975**	**253**
Annual				**4666150.875**	**92345**

Generation and Loss Data in 2015 With 100 MW Wind					
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	NO	453.92	7.05	226.96	3.525
12:30:00 AM	NO	464.56	7.29	232.28	3.645
01:00:00 AM	NO	476.67	7.6	238.335	3.8
01:30:00 AM	NO	488.35	7.94	244.175	3.97
02:00:00 AM	NO	500.14	8.3	250.07	4.15
02:30:00 AM	NO	511.61	8.69	255.805	4.345
03:00:00 AM	NO	522.46	9.07	261.23	4.535
03:30:00 AM	NO	532.88	9.47	266.44	4.735
04:00:00 AM	NO	544.02	9.96	272.01	4.98
04:30:00 AM	NO	555.93	10.51	277.965	5.255
05:00:00 AM	NO	567.03	11.03	283.515	5.515
05:30:00 AM	NO	575.88	11.54	287.94	5.77
06:00:00 AM	NO	587.4	12.16	293.7	6.08
06:30:00 AM	NO	598.06	12.84	299.03	6.42
07:00:00 AM	NO	609.36	13.53	304.68	6.765
07:30:00 AM	NO	621.99	14.32	310.995	7.16
08:00:00 AM	NO	635.41	15.26	317.705	7.63
08:30:00 AM	NO	655.09	16.43	327.545	8.215
09:00:00 AM	NO	673.68	17.57	336.84	8.785
09:30:00 AM	NO	667.4	17.72	333.7	8.86
10:00:00 AM	NO	685.05	18.93	342.525	9.465
10:30:00 AM	NO	702.31	20.16	351.155	10.08
11:00:00 AM	NO	722.56	21.81	361.28	10.905
11:30:00 AM	NO	721.17	21.65	360.585	10.825
12:00:00 PM	NO	718.98	21.47	359.49	10.735
12:30:00 PM	NO	707.59	20.84	353.795	10.42
01:00:00 PM	NO	705.52	20.68	352.76	10.34
01:30:00 PM	NO	702.16	20.49	351.08	10.245
02:00:00 PM	NO	699.96	20.31	349.98	10.155
02:30:00 PM	NO	698.2	20.07	349.1	10.035

Generation and Loss Data in 2015 With 100 MW Wind					
Simulation Time	**Skip**	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
03:00:00 PM	NO	694.97	19.85	347.485	9.925
03:30:00 PM	NO	701.07	19.6	350.535	9.8
04:00:00 PM	NO	702.85	19.37	351.425	9.685
04:30:00 PM	NO	705.9	19.15	352.95	9.575
05:00:00 PM	NO	709.26	19.02	354.63	9.51
05:30:00 PM	NO	729.02	19.58	364.51	9.79
06:00:00 PM	NO	731.67	19.49	365.835	9.745
06:30:00 PM	NO	740.88	19.86	370.44	9.93
07:00:00 PM	NO	743.3	19.88	371.65	9.94
07:30:00 PM	NO	730.77	19.06	365.385	9.53
08:00:00 PM	NO	719.58	18.33	359.79	9.165
08:30:00 PM	NO	709	17.63	354.5	8.815
09:00:00 PM	NO	698.3	16.91	349.15	8.455
09:30:00 PM	NO	688.18	16.4	344.09	8.2
10:00:00 PM	NO	676.24	15.66	338.12	7.83
10:30:00 PM	NO	666.59	15.11	333.295	7.555
11:00:00 PM	NO	656.63	14.63	328.315	7.315
11:30:00 PM	NO	652.69	14.61	326.345	7.305
Daily				**15481.12**	**379.415**
Annual				**5650608.8**	**138486.475**

Output of fossil fuel units and the corresponding system losses for Jamaica's transmission network with the inclusion of 50 MW blocks of EG for 2015 system loading

Region	Lucea			
Simulation Time	Total Generator Output (MW)	Total System Loss (MW)	Energy Consumed (MWh)	Energy Loss (MWh)
12:00:00 AM	460.08	7.43	230.04	3.715
12:30:00 AM	470.78	7.69	235.39	3.845
01:00:00 AM	482.86	8.02	241.43	4.01
01:30:00 AM	493.93	8.34	246.965	4.17
02:00:00 AM	505.8	8.72	252.9	4.36
02:30:00 AM	517.26	9.13	258.63	4.565
03:00:00 AM	528.1	9.52	264.05	4.76
03:30:00 AM	538.65	10.02	269.325	5.01
04:00:00 AM	549.81	10.54	274.905	5.27
04:30:00 AM	561.74	11.11	280.87	5.555
05:00:00 AM	572.86	11.66	286.43	5.83
05:30:00 AM	584.82	12.3	292.41	6.15
06:00:00 AM	596.36	12.94	298.18	6.47
06:30:00 AM	606.73	13.7	303.365	6.85
07:00:00 AM	618.05	14.41	309.025	7.205
07:30:00 AM	631.33	15.27	315.665	7.635
08:00:00 AM	644.75	16.2	322.375	8.1
08:30:00 AM	663.01	17.34	331.505	8.67
09:00:00 AM	681.67	18.52	340.835	9.26
09:30:00 AM	691.97	20.34	345.985	10.17
10:00:00 AM	709.52	21.4	354.76	10.7
10:30:00 AM	728.1	22.78	364.05	11.39
11:00:00 AM	749.39	24.72	374.695	12.36
11:30:00 AM	746.58	24.46	373.29	12.23
12:00:00 PM	744.28	24.2	372.14	12.1
12:30:00 PM	735.19	24.37	367.595	12.185
01:00:00 PM	733.01	24.19	366.505	12.095

Region	Lucea			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
01:30:00 PM	730.2	23.98	365.1	11.99
02:00:00 PM	727.97	23.76	363.985	11.88
02:30:00 PM	726.4	23.48	363.2	11.74
03:00:00 PM	723.12	23.22	361.56	11.61
03:30:00 PM	731.91	22.56	365.955	11.28
04:00:00 PM	733.89	22.37	366.945	11.185
04:30:00 PM	736.1	22.17	368.05	11.085
05:00:00 PM	739.5	22.1	369.75	11.05
05:30:00 PM	741.16	21.91	370.58	10.955
06:00:00 PM	743.2	21.78	371.6	10.89
06:30:00 PM	753.95	21.46	376.975	10.73
07:00:00 PM	756.49	21.48	378.245	10.74
07:30:00 PM	745.18	20.65	372.59	10.325
08:00:00 PM	733.9	19.85	366.95	9.925
08:30:00 PM	722.69	19.1	361.345	9.55
09:00:00 PM	711.94	18.39	355.97	9.195
09:30:00 PM	700.88	17.65	350.44	8.825
10:00:00 PM	689.07	16.91	344.535	8.455
10:30:00 PM	678.56	16.31	339.28	8.155
11:00:00 PM	668.57	15.77	334.285	7.885
11:30:00 PM	658.88	15.24	329.44	7.62
Daily			**15850.1**	**419.73**
Annual			**5785285**	**153201.5**

Region	Robins Bay			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	456.05	7.15	228.025	3.575
12:30:00 AM	466.74	7.41	233.37	3.705
01:00:00 AM	478.81	7.74	239.405	3.87
01:30:00 AM	490.28	8.09	245.14	4.045
02:00:00 AM	502.15	8.47	251.075	4.235
02:30:00 AM	513.59	8.88	256.795	4.44
03:00:00 AM	524.51	9.28	262.255	4.64
03:30:00 AM	535.99	9.73	267.995	4.865
04:00:00 AM	547.11	10.25	273.555	5.125
04:30:00 AM	559	10.82	279.5	5.41
05:00:00 AM	570.17	11.36	285.085	5.68
05:30:00 AM	579.42	11.86	289.71	5.93
06:00:00 AM	590.93	12.5	295.465	6.25
06:30:00 AM	602.42	13.19	301.21	6.595
07:00:00 AM	613.72	13.89	306.86	6.945
07:30:00 AM	626.43	14.71	313.215	7.355
08:00:00 AM	639.86	15.65	319.93	7.825
08:30:00 AM	659.36	16.76	329.68	8.38
09:00:00 AM	678.07	17.92	339.035	8.96
09:30:00 AM	680.58	18.32	340.29	9.16
10:00:00 AM	698.13	19.4	349.065	9.7
10:30:00 AM	715.62	20.67	357.81	10.335
11:00:00 AM	735.81	22.22	367.905	11.11
11:30:00 AM	734.1	22.01	367.05	11.005
12:00:00 PM	731.95	21.84	365.975	10.92
12:30:00 PM	728.02	21.59	364.01	10.795

Region	Robins Bay			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
01:00:00 PM	725.84	21.42	362.92	10.71
01:30:00 PM	722.5	21.23	361.25	10.615
02:00:00 PM	720.27	21.04	360.135	10.52
02:30:00 PM	718.45	20.9	359.225	10.45
03:00:00 PM	715.18	20.66	357.59	10.33
03:30:00 PM	717.34	20.4	358.67	10.2
04:00:00 PM	719.3	20.19	359.65	10.095
04:30:00 PM	722.11	19.98	361.055	9.99
05:00:00 PM	725.41	19.83	362.705	9.915
05:30:00 PM	742.35	20.49	371.175	10.245
06:00:00 PM	744.39	20.39	372.195	10.195
06:30:00 PM	746.26	20.28	373.13	10.14
07:00:00 PM	749.38	20.29	374.69	10.145
07:30:00 PM	736.62	19.47	368.31	9.735
08:00:00 PM	725.39	18.74	362.695	9.37
08:30:00 PM	714.66	18.08	357.33	9.04
09:00:00 PM	703.97	17.42	351.985	8.71
09:30:00 PM	692.22	16.7	346.11	8.35
10:00:00 PM	680.36	16.02	340.18	8.01
10:30:00 PM	670.3	15.45	335.15	7.725
11:00:00 PM	660.32	14.93	330.16	7.465
11:30:00 PM	655.7	14.83	327.85	7.415
Daily			**15683.6**	**390.225**
Annual			**5724503**	**142432.1**

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Output of fossil fuel units and the corresponding system losses for Jamaica's transmission network with the inclusion of 100 MW blocks of EG for 2015 system loading

Region	**Morant Point**			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	456.43	7.2	228.215	3.6
12:30:00 AM	467.13	7.44	233.565	3.72
01:00:00 AM	479.2	7.75	239.6	3.875
01:30:00 AM	490.25	8.06	245.125	4.03
02:00:00 AM	502.11	8.42	251.055	4.21
02:30:00 AM	513.51	8.8	256.755	4.4
03:00:00 AM	524.39	9.18	262.195	4.59
03:30:00 AM	535.48	9.6	267.74	4.8
04:00:00 AM	546.55	10.09	273.275	5.045
04:30:00 AM	558.41	10.63	279.205	5.315
05:00:00 AM	569.59	11.16	284.795	5.58
05:30:00 AM	581.48	11.77	290.74	5.885
06:00:00 AM	593.03	12.39	296.515	6.195
06:30:00 AM	604.88	13.07	302.44	6.535
07:00:00 AM	616.2	13.75	308.1	6.875
07:30:00 AM	629.43	14.57	314.715	7.285
08:00:00 AM	642.86	15.48	321.43	7.74
08:30:00 AM	661.42	16.58	330.71	8.29
09:00:00 AM	680.06	17.72	340.03	8.86
09:30:00 AM	686.2	17.85	343.1	8.925
10:00:00 AM	703.82	19.09	351.91	9.545
10:30:00 AM	721.4	20.39	360.7	10.195
11:00:00 AM	743.47	21.96	371.735	10.98
11:30:00 AM	740.55	21.81	370.275	10.905
12:00:00 PM	738.31	21.63	369.155	10.815

Region	Morant Point			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:30:00 PM	714.89	21.07	357.445	10.535
01:00:00 PM	712.76	20.92	356.38	10.46
01:30:00 PM	710.04	20.77	355.02	10.385
02:00:00 PM	707.87	20.62	353.935	10.31
02:30:00 PM	706.01	20.47	353.005	10.235
03:00:00 PM	702.81	20.27	351.405	10.135
03:30:00 PM	709.92	20.07	354.96	10.035
04:00:00 PM	711.82	19.95	355.91	9.975
04:30:00 PM	715.37	19.81	357.685	9.905
05:00:00 PM	718.81	19.78	359.405	9.89
05:30:00 PM	720.49	19.68	360.245	9.84
06:00:00 PM	722.66	19.65	361.33	9.825
06:30:00 PM	742.19	19.83	371.095	9.915
07:00:00 PM	744.58	19.89	372.29	9.945
07:30:00 PM	732.86	19.14	366.43	9.57
08:00:00 PM	721.64	18.39	360.82	9.195
08:30:00 PM	710.47	17.68	355.235	8.84
09:00:00 PM	699.76	17	349.88	8.5
09:30:00 PM	695.8	16.81	347.9	8.405
10:00:00 PM	683.87	16.11	341.935	8.055
10:30:00 PM	674.63	15.63	337.315	7.815
11:00:00 PM	664.74	15.12	332.37	7.56
11:30:00 PM	653.75	14.5	326.875	7.25
			15632	**384.775**
			5705662	**140443**

Region	Wigton			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:00:00 AM	451.62	7.19	225.81	3.595
12:30:00 AM	462.34	7.45	231.17	3.725
01:00:00 AM	474.42	7.77	237.21	3.885
01:30:00 AM	486.35	8.11	243.175	4.055
02:00:00 AM	498.18	8.49	249.09	4.245
02:30:00 AM	509.63	8.89	254.815	4.445
03:00:00 AM	520.45	9.29	260.225	4.645
03:30:00 AM	531.62	9.75	265.81	4.875
04:00:00 AM	542.72	10.26	271.36	5.13
04:30:00 AM	554.65	10.83	277.325	5.415
05:00:00 AM	565.79	11.37	282.895	5.685
05:30:00 AM	572.69	11.97	286.345	5.985
06:00:00 AM	584.08	12.62	292.04	6.31
06:30:00 AM	595.15	13.33	297.575	6.665
07:00:00 AM	606.44	14.04	303.22	7.02
07:30:00 AM	618.59	14.9	309.295	7.45
08:00:00 AM	632	15.81	316	7.905
08:30:00 AM	652.47	16.82	326.235	8.41
09:00:00 AM	671.1	17.96	335.55	8.98
09:30:00 AM	660.66	19.56	330.33	9.78
10:00:00 AM	677.33	20.65	338.665	10.325
10:30:00 AM	693.99	22.08	346.995	11.04
11:00:00 AM	714.98	23.56	357.49	11.78
11:30:00 AM	713.04	23.56	356.52	11.78
12:00:00 PM	710.86	23.37	355.43	11.685

Region	**Wigton**			
Simulation Time	**Total Generator Output (MW)**	**Total System Loss (MW)**	**Energy Consumed (MWh)**	**Energy Loss (MWh)**
12:30:00 PM	706.23	23.18	353.115	11.59
01:00:00 PM	704.01	23.01	352.005	11.505
01:30:00 PM	700.15	22.89	350.075	11.445
02:00:00 PM	697.93	22.69	348.965	11.345
02:30:00 PM	696.04	22.52	348.02	11.26
03:00:00 PM	692.77	22.28	346.385	11.14
03:30:00 PM	694.99	22.02	347.495	11.01
04:00:00 PM	696.89	21.79	348.445	10.895
04:30:00 PM	700.26	21.51	350.13	10.755
05:00:00 PM	703.61	21.4	351.805	10.7
05:30:00 PM	733.72	20.9	366.86	10.45
06:00:00 PM	736.39	20.79	368.195	10.395
06:30:00 PM	738.45	20.67	369.225	10.335
07:00:00 PM	741	20.69	370.5	10.345
07:30:00 PM	726.6	19.88	363.3	9.94
08:00:00 PM	716.28	19.03	358.14	9.515
08:30:00 PM	705.9	18.31	352.95	9.155
09:00:00 PM	695.15	17.61	347.575	8.805
09:30:00 PM	682.97	16.86	341.485	8.43
10:00:00 PM	671.12	16.14	335.56	8.07
10:30:00 PM	661.42	15.51	330.71	7.755
11:00:00 PM	651.3	14.93	325.65	7.465
11:30:00 PM	651.17	14.82	325.585	7.41
			15402.8	**404.53**
			5622004	**147653**

Bus voltages for load and generator buses at peak demand in 2008

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
1	1	69	0.95857	40.46	4.84	2.56			0
2	3	138	0.9833	17.05					0
3	1	69	0.9675	42.3					0
4	1	69	0.96971	41.69	1.34	0.13			0
5	3	138	1.00011	20.81					0
6	1	69	0	0					0
7	1	69	0	0					0
8	1	69	1.00002	54.68	28.72	6.8			0
9	2	11.5	0.9405	87.67			11.17	0.78	0
10	4	11.5	0.94839	86.54			9.31	4.5	0
11	4	11.5	0.93745	89.71			16.61	0.95	0
12	4	11.5	0.95202	87.15			9.99	4.5	0
13	4	11.5	0.93679	87.06			9.31	0.79	0
14	2	69	0.98465	40.8	9.44	2.82			2.91
15	1	69	0.9533	43.09	16.73	1.55			5.09
16	1	6.9	1.01108	19.17			5.93	4.45	0
19	1	6.9	1.00627	78.36			2.35	1.76	0
20	2	69	0.97515	40.79	31.26	9.22			0
21	3	138	0.99347	15.26					0
22	2	69	0.99117	41.95	4.71	3.59			0
23	3	138	0.98936	18.59					0
24	4	69	0.96439	46.72	5.2	2.08			0
25	1	69	0.99501	45.04	5.82	4.34			0
26	2	69	0.94782	38.76	9.25	2.7			0
27	4	69	0.96104	49.33	2.69	1.1			0
28	2	69	0.99851	41.47	15.86	0.07			0
29	1	69	0.96213	40.87	5.7	1.34			0
30	2	69	0.97367	40.3	24.66	17.22			0
31	1	11.5	1.0487	73.79			16.47	20.19	0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
32	2	69	1.00001	41.62					0
33	2	69	1.00001	41.62	46.18	2.45			0
34	2	69	1.00001	41.62					0
35	2	69	1.00001	41.62					0
37	2	69	1.00001	41.62					0
38	1	13.8	1	75.44			44.9	0.09	0
39	1	11.5	0.98647	73.89			10.69	13.46	0
40	1	11.5	1.00224	87.57			39.5	1.5	0
41	1	11.5	1.00216	87.35			39.5	1.5	0
43	1	11.5	1.00238	88.13			39.5	1.5	0
44	1	69	0	0					0
45	1	11.5	1.01958	73.72			10.69	23.25	0
46	1	69	0.99638	44.45					0
47	3	138	0.99205	17.92					0
48	1	69	0.98285	46.43	6.74	2.32			0
49	1	69	0.9595	42.19					0
50	1	6.9	0.96983	46.58			4.5	1	0
53	2	69	0.94603	38.71	3.08	2.32			0
54	1	69	0.97547	46.65	10.67	2.32			0
55	1	69	0.97908	46.17					0
56	1	69	0.96147	47.72	3.71	1.52			0
57	4	69	0.96991	44.81	9.88	4.89			0
58	1	69	0.9685	41.47	15.95	4.03			0
59	1	69	0.98029	44.76	7.15	3.95			0
60	1	69	0.95276	42.01	13.49	6.91			0
61	3	138	1.01002	18.87					0
62	1	69	0	0					0
63	1	69	0	0					0
67	1	69	1.00232	45.29					0
69	1	13.8	1.05102	53.47			58.5	30	0
70	4	13.8	1.04926	52.05			44.07	30	0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
71	1	13.8	0.97354	80.07			30.15	5	0
72	1	13.8	1.05115	53.08			53.9	30	0
73	1	69	0.95681	41.34	5.93	2.24			0
74	1	69	0.96737	49.72	22.6	9.37			4.68
75	3	138	1.00296	18.44					0
76	1	69	0.97823	45.03	16.24	5.13			0
77	1	69	0.96611	38.38	7.52	3.93			9.33
78	2	69	0.97662	41.18	19.08	8.35			0
79	1	69	0.96965	45.08	10.85	3.22			0
80	1	69	0.97003	52.56	25.52	8.83			4.7
81	1	69	0.99405	44.52	13.74	4.98			0
82	1	69	0.9606	45.2					0
83	1	69	0.95075	42.14	10.79	4.26			0
84	2	69	1.00001	41.81	6.11	2.17			0
85	1	69	0.96294	50.96	9.44	2.11			0
86	1	69	0.97416	49.25	19.5	0.83			4.56
87	3	138	0.99078	17.78					0
88	1	69	0.97667	46	15.25	6.43			0
89	1	69	0.98104	42.36	3.97	2.48			0
90	1	69	0.96873	41.51					0
91	2	69	0.99211	41.1	22.52	0			0
92	1	69	0.97288	45.08					0
93	3	138	0.98912	17.11					0
94	4	69	0.98131	42.17	12.85	4.52			0
95	1	69	0.97939	41.84	26.56	10.92			0
96	2	69	0.99091	41.05	18.9	1.81			0
97	4	69	0.96289	42.24	3.29	1.19			0
98	4	6.9	1.00629	45.23			3.39	2.54	0
99	2	69	0.98637	40.95	32.57	2.04			0
100	1	69	0.99218	44.97	7.56	4.71			0
101	2	69	0.98449	40.71	17.07	0			0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
102	1	69	0.99753	44.73	4.21	2.6			0
103	1	69	0	0					0
104	2	13.8	1.02424	75.61			18.37	6.39	0
105	2	13.8	1.02424	75.61			18.37	6.39	0
106	2	13.8	1.01766	74.93			27.39	8.51	0
107	2	13.8	1.01977	74.92			27.39	9.58	0
108	1	69	0	0					0
118	1	11	1.00923	53.55			34.16	0	0
119	1	11	1.00959	53.11			30.93	0	0
121	1	13.8	0.93166	45.03			0	0	0
122	1	11.5	1.00505	86.52			13.7	1.67	0
123	2	69	0.99517	41.5	2.43	1.57			0
124	2	69	0.995	41.78	2.43	1.57			0
125	4	69	0	0					0
126	1	69	0.97824	45.03					0
127	1	6.9	1.00761	46.16			4	3	0

Bus voltages for load and generator buses at peak demand in 2015

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
1	1	69	0.927	38.54	5.75	3.04			0
2	3	138	0.9668	16.51					0
3	1	69	0.9411	40.66					0
4	1	69	0.9449	40.03	1.59	0.15			0
5	3	138	0.9923	21.04					0
6	1	69	0	0					0
7	1	69	0	0					0
8	1	69	1	55.75	34.14	8.08			0
9	2	11.5	0.9443	89.96			15.82	1.74	0
10	4	11.5	0.9668	88.5			14.18	10.18	0
11	4	11.5	0.9416	92.59			22.72	2.13	0
12	4	11.5	0.9745	89.11			14.09	10.22	0
13	4	11.5	0.9407	89.35			14.18	1.76	0
14	2	69	0.9804	39.03	11.22	3.35			2.88
15	1	69	0.9237	41.58	19.88	1.84			4.78
16	1	6.9	0.9921	18.52			5.93	4.45	0
19	1	6.9	0.9822	77.53			2.35	1.76	0
20	2	69	0.963	39.12	37.16	10.96			0
21	3	138	0.9824	14.38					0
22	2	69	0.9824	40.53	5.6	4.27			0
23	3	138	0.9755	18.37					0
24	4	69	0.9432	46.07	6.18	2.47			0
25	1	69	0.9739	44.23	6.92	5.16			0
26	2	69	0.9358	36.57	11	3.21			0
27	4	69	0.9442	49.31	3.2	1.3			0
28	2	69	0.9959	39.96	18.85	0.09			0
29	1	69	0.9334	39.03	6.77	1.59			0
30	2	69	0.9661	38.46	29.31	20.47			0
31	1	11.5	1.047	73.46			24.3	21	0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
32	2	69	0.9967	40.21					3.97
33	2	69	0.9967	40.21	54.9	2.92			0
34	2	69	0.9967	40.21					0
35	2	69	0.9967	40.21					0
37	2	69	0.9967	40.21					0
38	1	13.8	1	75.44			61.32	3.14	0
39	1	11.5	0.9852	73.67			15.95	14	0
40	1	11.5	1.0045	88.88			43	3.35	0
41	1	11.5	1.0043	88.65			43	3.35	0
43	1	11.5	1.005	89.49			43	3.35	0
44	1	69	0	0					0
45	1	11.5	1.0207	73.45			15.95	24.5	0
46	1	69	0.976	43.54					0
47	3	138	0.9773	17.5					0
48	1	69	0.9654	45.66	8.02	2.75			0
49	1	69	0.9304	40.47					0
50	1	6.9	0.9415	45.13			4.5	1	0
53	2	69	0.9337	36.51	3.67	2.75			0
54	1	69	0.9558	45.9	12.68	2.75			0
55	1	69	0.9606	45.33					0
56	1	69	0.9416	47.32	4.41	1.81			0
57	4	69	0.9475	43.71	11.74	5.82			0
58	1	69	0.9447	39.8	18.96	4.79			0
59	1	69	0.9581	43.77	8.5	4.7			0
60	1	69	0.922	40.24	16.03	8.22			0
61	3	138	1	18.6					0
62	1	69	0	0					0
63	1	69	0	0					0
67	1	69	0.9823	44.57					0
69	1	13.8	1.0409	53.69			63.5	30	0
70	4	13.8	1.0389	53.04			59.98	30	0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
71	1	13.8	0.9532	80.86			38	5	0
72	1	13.8	1.0411	53.26			58.5	30	0
73	1	69	0.9268	39.55	7.05	2.67			0
74	1	69	0.9539	49.81	26.86	11.14			4.55
75	3	138	0.9909	18.1					0
76	1	69	0.9577	43.98	19.3	6.1			0
77	1	69	0.927	36.12	8.93	4.67			8.59
78	2	69	0.9649	39.6	22.68	9.93			0
79	1	69	0.9482	44.01	12.9	3.83			0
80	1	69	0.9607	53.28	30.34	10.5			4.61
81	1	69	0.9727	43.62	16.33	5.92			0
82	1	69	0.9355	44.19					0
83	1	69	0.9194	40.38	12.83	5.07			0
84	2	69	1	40.21	7.26	2.58			0
85	1	69	0.9496	51.32	11.22	2.5			0
86	1	69	0.9606	49.22	23.18	0.99			4.43
87	3	138	0.9756	17.33					0
88	1	69	0.9575	45.13	18.12	7.64			0
89	1	69	0.9609	40.93	4.71	2.95			0
90	1	69	0.9447	39.84					0
91	2	69	0.9867	39.54	26.78	0			0
92	1	69	0.9517	44.02					0
93	3	138	0.9752	16.55					0
94	4	69	0.9616	40.7	15.27	5.38			0
95	1	69	0.9623	40.33	31.58	12.98			0
96	2	69	0.9876	39.34	22.47	2.15			0
97	4	69	0.9348	40.55	3.91	1.41			0
98	4	6.9	0.9793	43.72			3.39	2.54	0
99	2	69	0.9793	39.3	38.71	2.43			0
100	1	69	0.9707	44.14	8.98	5.6			0
101	2	69	0.9784	38.98	20.29	0			0

Bus Num	Zone Num	Bus Nom Volt	Bus PU Volt	Bus Angle	Bus Load MW	Bus Load MVR	Bus Gen MW	Bus Gen MVR	Shunt
102	1	69	0.9769	43.88	5.01	3.09			0
103	1	69	0	0					0
104	2	13.8	1.0431	74.22			20	11.76	0
105	2	13.8	1.0431	74.22			20	11.76	0
106	2	13.8	1.0315	73.62			30.6	15.68	0
107	2	13.8	1.0353	73.6			30.6	17.64	0
108	1	69	0	0					0
118	1	11	1.0245	53.61			37.08	10.75	0
119	1	11	1.0249	53.18			33.91	10.75	0
121	1	13.8	0.9121	43.98			0	0	0
122	1	11.5	1.01	88.26			18.82	3.73	0
123	2	69	0.9939	39.85	2.88	1.87			0
124	2	69	0.9888	40.36	2.89	1.87			0
125	4	69	0	0					0
126	1	69	0.9577	43.98					0
127	1	6.9	0.9779	44.66			4	3	0

Per unit bus voltages for time step simulation

Simulation Time	Skip	Bus #1 pu Volt	Bus #4 pu Volt	Bus #8 pu Volt	Bus #14 pu Volt	Bus #15 pu Volt	Bus #20 pu Volt	Bus #22 pu Volt
12:00:00 AM	NO	0.98	0.99	1.02	0.99	0.99	0.98	1
12:30:00 AM	NO	0.98	0.99	1.02	0.99	0.99	0.98	1
01:00:00 AM	NO	0.98	0.99	1.02	0.99	0.98	0.98	1
01:30:00 AM	NO	0.98	0.99	1.01	0.99	0.98	0.98	1
02:00:00 AM	NO	0.97	0.98	1.01	0.99	0.97	0.98	1
02:30:00 AM	NO	0.97	0.98	1	0.99	0.97	0.98	0.99
03:00:00 AM	NO	0.97	0.98	1	0.99	0.97	0.98	0.99
03:30:00 AM	NO	0.97	0.98	1	0.99	0.97	0.98	0.99
04:00:00 AM	NO	0.97	0.98	1	0.99	0.96	0.98	0.99
04:30:00 AM	NO	0.97	0.98	1	0.99	0.96	0.98	0.99
05:00:00 AM	NO	0.96	0.97	1	0.99	0.96	0.98	0.99
05:30:00 AM	NO	0.96	0.97	1	0.99	0.96	0.98	0.99
06:00:00 AM	NO	0.96	0.97	1	0.99	0.96	0.98	0.99
06:30:00 AM	NO	0.96	0.97	1	0.99	0.95	0.98	0.99
07:00:00 AM	NO	0.96	0.97	1	0.99	0.95	0.98	0.99
07:30:00 AM	NO	0.96	0.97	1	0.99	0.95	0.97	0.99
08:00:00 AM	NO	0.95	0.96	1	0.99	0.95	0.97	0.99
08:30:00 AM	NO	0.95	0.96	1	0.99	0.94	0.97	0.99
09:00:00 AM	NO	0.95	0.96	1	0.99	0.94	0.97	0.98
09:30:00 AM	NO	0.94	0.95	1	0.98	0.93	0.97	0.98
10:00:00 AM	NO	0.94	0.95	1	0.98	0.93	0.96	0.98
10:30:00 AM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97
11:00:00 AM	NO	0.92	0.94	1	0.97	0.92	0.95	0.97
11:30:00 AM	NO	0.93	0.94	1	0.97	0.92	0.95	0.97
12:00:00 PM	NO	0.93	0.94	1	0.97	0.92	0.95	0.97
12:30:00 PM	NO	0.93	0.94	1	0.97	0.92	0.95	0.97
01:00:00 PM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97
01:30:00 PM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97
02:00:00 PM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97

Simulation Time	Skip	Bus #1 pu Volt	Bus #4 pu Volt	Bus #8 pu Volt	Bus #14 pu Volt	Bus #15 pu Volt	Bus #20 pu Volt	Bus #22 pu Volt
02:30:00 PM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97
03:00:00 PM	NO	0.93	0.94	1	0.97	0.92	0.96	0.97
03:30:00 PM	NO	0.93	0.94	1	0.98	0.92	0.96	0.98
04:00:00 PM	NO	0.93	0.95	1	0.98	0.92	0.96	0.98
04:30:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
05:00:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
05:30:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
06:00:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
06:30:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
07:00:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
07:30:00 PM	NO	0.93	0.95	1	0.98	0.93	0.96	0.98
08:00:00 PM	NO	0.94	0.95	1	0.98	0.93	0.97	0.98
08:30:00 PM	NO	0.94	0.95	1	0.98	0.93	0.97	0.98
09:00:00 PM	NO	0.94	0.95	1	0.98	0.94	0.97	0.99
09:30:00 PM	NO	0.95	0.96	1	0.99	0.94	0.97	0.99
10:00:00 PM	NO	0.95	0.96	1	0.99	0.94	0.97	0.99
10:30:00 PM	NO	0.95	0.96	1	0.99	0.94	0.97	0.99
11:00:00 PM	NO	0.95	0.96	1	0.99	0.94	0.97	0.99
11:30:00 PM	NO	0.96	0.96	1	0.99	0.94	0.97	0.99

Pu bus voltages at peak demand for the years studied

Year	2008	2010	2012	2015	2020
Bus Number	**pu Volt**				
1	0.95857	0.94815	0.94112	0.92704	0.91205
4	0.96971	0.96117	0.95527	0.94494	0.93919
8	1.00002	1	1	1.00001	1
14	0.98465	0.98326	0.97888	0.98043	0.95888
15	0.9533	0.94457	0.93886	0.92372	0.90337
20	0.97515	0.96935	0.96437	0.96304	0.94712
22	0.99117	0.98536	0.98184	0.98239	0.97278
24	0.96439	0.95749	0.95128	0.94316	0.92735
25	0.99501	0.99059	0.98887	0.9739	0.98368
26	0.94782	0.94268	0.93369	0.93582	0.89681
27	0.96104	0.95249	0.94214	0.94419	0.91419
28	0.99851	0.99788	0.99678	0.99594	0.99341
29	0.96213	0.95359	0.94515	0.9334	0.92402
30	0.97367	0.96826	0.96292	0.96613	0.94506
33	1.00001	0.9992	0.9977	0.99665	0.99413
48	0.98285	0.97524	0.96994	0.96544	0.95719
53	0.94603	0.94063	0.93146	0.93366	0.89591
54	0.97547	0.96993	0.96482	0.95582	0.94733
56	0.96147	0.95344	0.94399	0.94164	0.92153
57	0.96991	0.96345	0.95962	0.94753	0.94294
58	0.9685	0.96051	0.95379	0.94467	0.93539
59	0.98029	0.97335	0.96825	0.95812	0.95352
60	0.95276	0.94388	0.93796	0.92204	0.90156
73	0.95681	0.94681	0.93913	0.92682	0.90469
74	0.96737	0.96025	0.95376	0.95385	0.93144
76	0.97823	0.97151	0.96765	0.95767	0.9502
77	0.96611	0.9591	0.95311	0.92701	0.9279
78	0.97662	0.97108	0.96604	0.96485	0.94782
79	0.96965	0.9608	0.95434	0.94817	0.93639

Year	2008	2010	2012	2015	2020
Bus Number	pu Volt				
80	0.97003	0.96747	0.96247	0.9607	0.94333
81	0.99405	0.98905	0.98518	0.97271	0.97569
83	0.95075	0.9427	0.93525	0.91943	0.8991
84	1.00001	1	1	1	0.9982
85	0.96294	0.95596	0.95109	0.94957	0.92706
86	0.97416	0.96869	0.96312	0.96056	0.94702
88	0.97667	0.97118	0.96732	0.95751	0.94992
89	0.98104	0.97373	0.96898	0.96094	0.95562
91	0.99211	0.98622	0.98221	0.98674	0.97353
94	0.98131	0.97421	0.9692	0.96164	0.95698
95	0.97939	0.97275	0.9681	0.96228	0.9533
96	0.99091	0.98419	0.98069	0.98761	0.96347
97	0.96289	0.95522	0.94945	0.93479	0.92691
99	0.98637	0.98346	0.97981	0.97934	0.96064
100	0.99218	0.9881	0.98279	0.97067	0.97537
101	0.98449	0.98266	0.97674	0.97841	0.9586
102	0.99753	0.9948	0.99441	0.97694	0.99104
123	0.99517	0.993	0.99074	0.99386	0.98399
124	0.995	0.98992	0.9886	0.98875	0.98241

Line violations resulting from generator contingencies

Generator Producing Violation	Number of Violations for 2015 Peak Load	Maximum Percent Overload	Number of Violations for 2012 Peak Load	Maximum Percent Overload	Number of Violations for 2010 Peak Load	Maximum Percent Overload	Number of Violations for 2008 Peak Load	Maximum Percent Overload
83	1	100			1	100	1	100
61	1	144.85	1	120.07	1	120.54	1	104.94
61	2	135.02	1	126.04	1	119.27	1	114.82
84	4	100.01	1	100				
84	4	100.01	1	100				
32	15	155.14	11	142.48	10	137.34	6	128.27
32	28	102.58						
32	28	100.35						
49	28	102.44	28	102.44	28	102.44	28	102.44
67	28	102.21						
2	29	120	15	109.84	1	103.74		
93	29	135.41	26	125.77	21	119.55	21	114.63

Line violations resulting from transformer contingencies

Year		2015	2012	2010	2008
From Bus Number	To Bus Number	Number of Violations	Number of Violations	Number of Violations	Number of Violations
8	10	1			
8	12	1			
61	70	1			
75	76	1			
5	8	2	1	1	
84	105	3			
84	104	3			
61	67	6	3	2	1
23	24	7	4	2	1
32	38	15			
83	127	25	14	5	4
2	3	117	65	16	8
93	94	123	81	78	75
32	31	124			
32	45	124			
49	50	124	83	83	83
67	71	124			

Bus voltage violations resulting from transformer contingencies

2015			2012			2010			2008		
Bus Number	Number of Violations	Minimum Voltage	Bus Number	Number of Violations	Minimum Voltage	Bus Number	Number of Violations	Minimum Voltage	Bus Number	Number of Violations	Minimum Voltage
1	1	0.89	57	1	0.87	57	1	0.88	57	1	0.9
15	3	0.89	71	1	0.9	76	1	0.89	121	1	0.87
24	1	0.9	76	1	0.88	121	1	0.85			
49	1	0.89	121	2	0.84	126	1	0.89			
57	1	0.86	126	1	0.88						
59	1	0.9									
60	2	0.89									
71	1	0.89									
73	1	0.89									
76	1	0.87									
77	1	0.89									
82	2	0.9									
83	2	0.89									

2015			2012			2010			2008		
Bus Number	**Number of Violations**	**Minimum Voltage**	**Bus Number**	**Number of Violations**	**Minimum Voltage**	**Bus Number**	**Number of Violations**	**Minimum Voltage**	**Bus Number**	**Number of Violations**	**Minimum Voltage**
92	1	0.89									
97	1	0.9									
121	2	0.83									
126	1	0.87									

Busbar fault levels resulting from increased system loading

Bus Number	Maximum Short Circuit Current (A) 2008	Maximum Short Circuit Current (A) 2015	Maximum Short Circuit Current (A) 2020	Nominal Voltage	Fault Level (MVA) for 2008 Loading	Fault Level (MVA) for 2015 Loading	Fault Level (MVA) for 2020 Loading
1	3104.18	3060.49	3034.54	69	371.0	365.8	362.7
4	6109.13	6070.8	6060.71	69	730.1	725.5	724.3
8	13648.1	13758.5	13838.9	69	1631.1	1644.3	1653.9
14	7256.25	7320.38	7373.98	69	867.2	874.9	881.3
15	3297.64	3246.73	3214.37	69	394.1	388.0	384.2
20	6080.17	6083.16	6096.14	69	1148.0	1161.6	1173.2
22	13610.8	13746.7	13900.5	69	726.7	727.0	728.6
24	4485.56	4437.98	4410.68	69	1364.5	1374.7	1386.8
25	5369.05	5328.75	5319.7	69	1626.6	1642.9	1661.3
26	1757.86	1758.65	1757.4	69	536.1	530.4	527.1
27	4208.11	4170.52	4145.15	69	641.7	636.8	635.8
28	10161.1	10250.6	10343.1	69	210.1	210.2	210.0
29	3684.16	3637.93	3611.66	69	502.9	498.4	495.4
30	6768.07	6816.4	6860.13	69	1214.4	1225.1	1236.1
33	14007.2	14176.4	14363.4	69	440.3	434.8	431.6
48	4400.99	4363.41	4359.35	69	808.9	814.6	819.9
53	1587.4	1586.59	1584.07	69	1674.0	1694.2	1716.6
54	3007.05	2973.21	2957.09	69	526.0	521.5	521.0
56	4110.12	4065.27	4036.83	69	189.7	189.6	189.3
57	3523.01	3481.67	3470.78	69	359.4	355.3	353.4
58	5232.52	5186.8	5166.22	69	491.2	485.8	482.4

Bus Number	Maximum Short Circuit Current (A) 2008	Maximum Short Circuit Current (A) 2015	Maximum Short Circuit Current (A) 2020	Nominal Voltage	Fault Level (MVA) for 2008 Loading	Fault Level (MVA) for 2015 Loading	Fault Level (MVA) for 2020 Loading
59	4197.75	4152.77	4138.77	69	421.0	416.1	414.8
60	4102.52	4052.81	4025.57	69	625.3	619.9	617.4
73	3385.67	3333	3301.12	69	501.7	496.3	494.6
74	3158.48	3156.79	3157.08	69	490.3	484.4	481.1
76	5195.63	5162.33	5169.16	69	404.6	398.3	394.5
77	1278.29	1250.76	1231.69	69	377.5	377.3	377.3
78	5449.6	5444.28	5448.6	69	441.5	440.0	439.3
79	3789.14	3746.28	3734.47	69	620.9	617.0	617.8
80	7139.25	7137.92	7138.1	69	152.8	149.5	147.2
81	4616.95	4574.28	4556.89	69	651.3	650.7	651.2
83	3699.16	3647.52	3616.72	69	452.8	447.7	446.3
84	11733.9	11903.7	12051	69	853.2	853.1	853.1
85	5109.5	5084.52	5067.49	69	551.8	546.7	544.6
86	3693.96	3681.64	3675.42	69	442.1	435.9	432.2
88	5280.07	5243.74	5244.91	69	1402.3	1422.6	1440.2
89	7730	7701.14	7707.53	69	610.6	607.7	605.6
91	10801.8	10891.7	10992.6	69	631.0	626.7	626.8
94	8928.23	8925.72	8957.6	69	923.8	920.4	921.1
95	9200.62	9207.18	9242.76	69	1290.9	1301.7	1313.7
96	9290.65	9386.83	9473.33	69	1067.0	1066.7	1070.5
97	4865.83	4816.72	4793.45	69	1099.6	1100.4	1104.6
99	11044.1	11144.5	11252.9	69	1110.3	1121.8	1132.2
100	5091.81	5049.74	5038.5	69	581.5	575.7	572.9

Bus Number	Maximum Short Circuit Current (A) 2008	Maximum Short Circuit Current (A) 2015	Maximum Short Circuit Current (A) 2020	Nominal Voltage	Fault Level (MVA) for 2008 Loading	Fault Level (MVA) for 2015 Loading	Fault Level (MVA) for 2020 Loading
101	9748.22	9840.93	9932.1	69	1319.9	1331.9	1344.9
102	5672.1	5631.52	5620.4	69	608.5	603.5	602.2
123	9605.43	9719.37	9816.35	69	1165.0	1176.1	1187.0
124	11416.9	11502.3	11603.8	69	677.9	673.0	671.7

Fault levels and the corresponding percentage increase for select buses in the vicinity of wind farms.

Bus Number	Fault Levels Without Wind Input	Fault Levels with 50 MW Wind Input	Fault Levels with 100 MW Wind Input	Percent Increase 50 MW Wind Input	Percent Increase 100 MW Wind Input
8	1644.3	**1709**	**1749**	**4**	2.34
14	874.9	**931**	**964**	**6**	3.50
123	1161.6	**1214**	**1244**	**5**	2.45
20	727	**740**	**747**	**2**	1.02
124	1374.7	**1418**	**1443**	**3**	1.77
22	1642.9	**1709**	**1748**	**4**	2.30
28	1225	**1260**	**1280**	**3**	1.57
30	814.6	**843**	**859**	**3**	1.88
37	1694	**1756**	**1792**	**4**	2.02
84	1422.6	**1480**	**1513**	**4**	2.20
91	1301.7	**1342**	**1364**	**3**	1.69
94	1066.7	**1126**	**1165**	**6**	3.50
95	1100.4	**1149**	**1180**	**4**	2.72
96	1121.8	**1158**	**1178**	**3**	1.76
99	1331.9	**1378**	**1404**	**3**	1.92
101	1176.1	**1217**	**1240**	**3**	1.91

Green house gas production levels for fossil fuel plants before the inclusion EG.

Heavy Fuel Oil Based Steam Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
2008								
Hunts Bay B6	41.6375	752.7678286	129.23053	55.06496666	2.2583035	0.451661	240.6975132	5776.740317
Old Harbour Gen 1	26.345625	289.6268341	49.721345	21.18620292	0.8688805	0.173776	92.60818022	2222.596325
Old Harbour Gen 2	48.03375	1088.40266	186.85024	79.6166546	3.265208	0.653042	348.0167506	8352.402015
Old Harbour Gen 3	52.139375	1347.948395	231.40745	98.60242507	4.0438452	0.808769	431.0064992	10344.15598
Old Harbour Gen 4	37.545	581.9317466	99.902446	42.56830726	1.7457952	0.349159	186.072676	4465.744223
	41.14025			**Daily Production**				**31161.63886**
				Annual Production				**11373998.18**
2010								
Hunts Bay B6	48.0670833	1090.371032	187.18816	79.76064099	3.2711131	0.654223	348.6461375	8367.5073

Heavy Fuel Oil Based Steam Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Old Harbour Gen 1	28.3070833	322.2845674	55.327823	23.57511611	0.9668537	0.193371	103.0504904	2473.21177
Old Harbour Gen 2	43.7152083	852.6138076	146.37147	62.36870002	2.5578414	0.511568	272.623265	6542.958359
Old Harbour Gen 3	52.4229167	1367.146214	234.70321	100.0067455	4.1014386	0.820288	437.1450019	10491.48005
Old Harbour Gen 4	43.88625	861.2268317	147.8501	62.99874274	2.5836805	0.516736	275.3772794	6609.054706
	43.279708			**Daily Production**				**34484.21218**
				Annual Production				**12586737.45**
2012								
Hunts Bay B6	51.86125	1329.277129	228.20208	97.23662201	3.9878314	0.797566	425.0363621	10200.87269
Old Harbour Gen 1	29.6925	350.094831	60.102117	25.60943689	1.0502845	0.210057	111.9428222	2686.627733
Old Harbour Gen 2	45.846875	964.2321616	165.53342	70.53358262	2.8926965	0.578539	308.3132337	7399.517608
Old Harbour Gen 3	54.7366667	1529.951506	262.65262	111.9159527	4.5898545	0.917971	489.2019941	11740.84786
Old Harbour Gen 4	46.2591667	986.8935589	169.42379	72.19126383	2.9606807	0.592136	315.5592155	7573.421171
	45.679292			**Daily Production**				**39601.28706**
				Annual Production				**14454469.78**

Heavy Fuel Oil Based Steam Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
2015								
Hunts Bay B6	55.2358333	1566.511405	268.929	114.5903093	4.6995342	0.939907	500.8920217	12021.40852
Old Harbour Gen 1	32.6952083	423.8492317	72.763817	31.0045713	1.2715477	0.25431	135.5257918	3252.619004
Old Harbour Gen 2	50.4710417	1238.32145	212.58737	90.58321408	3.7149644	0.742993	395.9532837	9502.878809
Old Harbour Gen 3	57.35375	1727.301825	296.5325	126.3521285	5.1819055	1.036381	552.3047585	13255.3142
Old Harbour Gen 4	51.405625	1299.031825	223.00976	95.02417797	3.8970955	0.779419	415.3654259	9968.770222
	49.432292			**Daily Production**				**48000.99076**
				Annual Production				**17520361.63**

Combined Cycle Automotive Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
2008								
Bogue GT 12	35.188333	299.595784	47.653193	23.6081351	0.898786869	0.179757374	97.48841574	2339.722
Bogue GT 13	35.188333	299.595784	47.653193	23.6081351	0.898786869	0.179757374	97.48841574	2339.722
	35.188333			**Daily Production**				**4679.44**
				Annual Production				**1707997**
2010								
Bogue GT 12	35.49	301.198641	47.90814	23.7344402	0.903595437	0.180719087	98.00998509	2352.24
Bogue GT 13	35.49	301.198641	47.90814	23.7344402	0.903595437	0.180719087	98.00998509	2352.24
	35.49			**Daily Production**				**4704.48**
				Annual Production				**1717135**
2012								
Bogue GT 12	37.0575	309.507289	49.2297	24.3891613	0.928521369	0.185704274	100.7136178	2417.127

Combined Cycle Automotive Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Bogue GT 13	37.0575	309.507289	49.2297	24.3891613	0.928521369	0.185704274	100.7136178	2417.127
	37.0575			**Daily Production**				**4834.25**
				Annual Production				**1764503**
2015								
Bogue GT 12	38.834375	318.885163	50.721328	25.1281374	0.956654977	0.191330995	103.7651765	2490.364
Bogue GT 13	38.834375	318.885163	50.721328	25.1281374	0.956654977	0.191330995	103.7651765	2490.364
	38.834375			**Daily Production**				**4980.73**
				Annual Production				**1817966**

Green house gas production levels for fossil fuel plants with the inclusion 100 MW of dispersed EG

Automotive Diesel Combustion Turbine Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Bogue GT3	13.435833	126.0510141	20.04945864	9.932814582	0.378152839	0.075630568	41.01698	984.4075
Bogue GT6	11.985833	117.6774294	18.71757058	9.27297646	0.353032099	0.07060642	38.29221	919.0132
Bogue GT7	10.573333	109.9100539	17.48210513	8.6609076	0.329729985	0.065945997	35.76471	858.3531
Bogue GT8	10.573333	109.9100539	17.48210513	8.6609076	0.329729985	0.065945997	35.76471	858.3531
Bogue GT9	18.195417	156.3852835	24.87437563	12.32315373	0.469155599	0.09383112	50.88774	1221.306
Bogue GT11	16.192917	143.0906786	22.75975853	11.27553943	0.429271806	0.085854361	46.56168	1117.48
Hunts Bay GT4	12.055	118.0676549	18.77963919	9.303726216	0.354202775	0.070840555	38.41919	922.0607
Hunts Bay GT5	12.055	118.0676549	18.77963919	9.303726216	0.354202775	0.070840555	38.41919	922.0607
Hunts Bay GT10	18.499167	158.4693903	25.2058701	12.48738126	0.475407916	0.095081583	51.56591	1237.582
				Daily Production				9040.616
				Annual Production				3299825

Green house gas production levels for fossil fuel plants with the inclusion 50 MW blocks of EG

Medium Speed Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Wigton								
Jamaica Enrgy Partners #1	32.295	295.4447232	46.99293219	23.2810317	0.886333694	0.177266739	96.13766135	2307.304
Jamaica Enrgy Partners #2	29.53770833	262.1989246	41.70491235	20.66126417	0.786596352	0.15731927	85.31948429	2047.668
Rocfort JP	26.653125	229.3045279	36.47278588	18.0691871	0.687913214	0.137582643	74.61565333	1790.776
Rocfort JP#2	26.653125	229.3045279	36.47278588	18.0691871	0.687913214	0.137582643	74.61565333	1790.776
Rockfort D1	17.42020833	136.983677	21.78838929	10.79430795	0.41095081	0.082190162	44.57446457	1069.787
Rockfort D2	17.42020833	136.983677	21.78838929	10.79430795	0.41095081	0.082190162	44.57446457	1069.787
				Daily Production				**10076.1**
				Annual Production				**3677775**

Medium Speed Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Rocky Point								
Jamaica Enrgy Partners #1	32.28666667	295.3415897	46.97652796	23.27290479	0.886024294	0.177204859	96.10410174	2306.498
Jamaica Enrgy Partners #2	29.530625	262.1157874	41.69168869	20.65471296	0.78634694	0.157269388	85.29243146	2047.018
Rocfort JP	26.646875	229.2353499	36.46178256	18.06373588	0.687705681	0.137541136	74.59314284	1790.235
Rocfort JP#2	26.646875	229.2353499	36.46178256	18.06373588	0.687705681	0.137541136	74.59314284	1790.235
Rockfort D1	17.41541667	136.9408948	21.78158444	10.79093672	0.410822464	0.082164493	44.56054327	1069.453
Rockfort D2	17.41541667	136.9408948	21.78158444	10.79093672	0.410822464	0.082164493	44.56054327	1069.453
				Daily Production				**10072.89**
				Annual Production				**3676606**

Medium Speed Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Robins Bay								
Jamaica Enrgy Partners #1	32.29666667	295.4653518	46.99621335	23.28265723	0.88639558	0.177279116	96.1443739	2307.465
Jamaica Enrgy Partners #2	29.53854167	262.2087062	41.7064682	20.66203497	0.786625697	0.157325139	85.32266723	2047.744
Rocfort JP	26.654375	229.3183645	36.47498672	18.07027743	0.687954724	0.137590945	74.62015578	1790.884
Rocfort JP#2	26.654375	229.3183645	36.47498672	18.07027743	0.687954724	0.137590945	74.62015578	1790.884
Rockfort D1	17.42125	136.9929781	21.78986872	10.79504089	0.410978714	0.082195743	44.57749117	1069.86
Rockfort D2	17.42125	136.9929781	21.78986872	10.79504089	0.410978714	0.082195743	44.57749117	1069.86
				Daily Production				10076.7
				Annual Production				3677994

Medium Speed Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Lucea								
Jamaica Enrgy Partners #1	32.625	299.5417484	47.64459802	23.60387711	0.898624763	0.179724953	97.47083265	2339.3
Jamaica Enrgy Partners #2	29.83958333	265.7528471	42.27019318	20.94131312	0.797258114	0.159451623	86.47593005	2075.422
Rocfort JP	26.925625	232.3294896	36.95393112	18.30755396	0.696988095	0.139397619	75.59997536	1814.399
Rocfort JP#2	26.925625	232.3294896	36.95393112	18.30755396	0.696988095	0.139397619	75.59997536	1814.399
Rockfort D1	17.59916667	138.5853085	22.04314206	10.92051645	0.415755702	0.08315114	45.0956352	1082.295
Rockfort D2	17.59916667	138.5853085	22.04314206	10.92051645	0.415755702	0.08315114	45.0956352	1082.295
				Daily Production				10208.11
				Annual Production				3725961

Medium Speed Diesel Units	Output	Heat Input (MBtu)	Volume (bbl/h)	CO_2 output (Mt/h)	Methane	Nitrous Oxide	$CO_{2[equivalent]}$	Total $CO_{2[equivalent]}$
Morant Point								
Jamaica Enrgy Partners #1	32.53520833	298.4244646	47.46688476	23.51583519	0.895272914	0.179054583	97.10726869	2330.574
Jamaica Enrgy Partners #2	29.7575	264.7844031	42.11615414	20.86499977	0.794352783	0.158870557	86.16079856	2067.859
Rocfort JP	26.85125	231.5021615	36.82233772	18.24236054	0.694506112	0.138901222	75.33076293	1807.938
Rocfort JP#2	26.85125	231.5021615	36.82233772	18.24236054	0.694506112	0.138901222	75.33076293	1807.938
Rockfort D1	17.55	138.1445398	21.97303414	10.88578389	0.414433397	0.082886679	44.95220912	1078.853
Rockfort D2	17.55	138.1445398	21.97303414	10.88578389	0.414433397	0.082886679	44.95220912	1078.853
				Daily Production				10172.02
				Annual Production				3712786

Appendix D - Weibull Analysis

Appendix C highlights the methodologies used by the Windographer programme used in this research. It considers the basis on which Weibull analysis was considered and the looks at the methods used in calculating the shape and scale factors for the distribution.

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Weibull Method for Wind Analysis

Wind analysts typically use the Weibull distribution to characterize the breadth of the distribution of wind speeds. The following equations give the **probability distribution function** and the **cumulative distribution function** of the two-parameter Weibull distribution:

$$f(U) = \frac{k}{c}\left(\frac{U}{c}\right)^{k-1} \times e\left[-\left(\frac{U}{c}\right)\right]^{k}$$

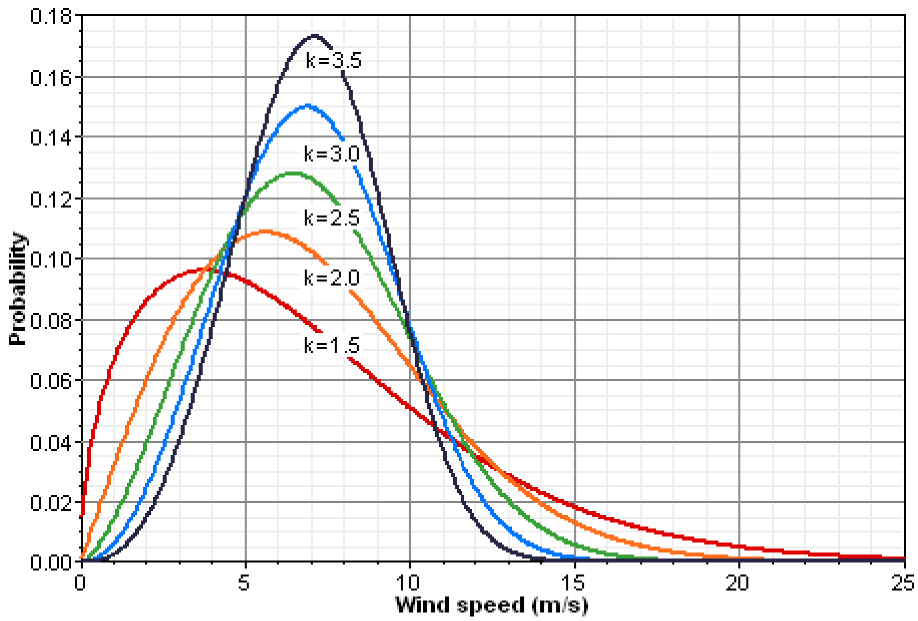
$$F(U) = 1 - e^{\left[-\left(\frac{U}{c}\right)^{k}\right]}$$

where U is the wind speed, k is a unit less shape factor, and c is a scale factor with the same units as U. The following equation gives the relationship between the scale factor c and the long-term average wind speed:

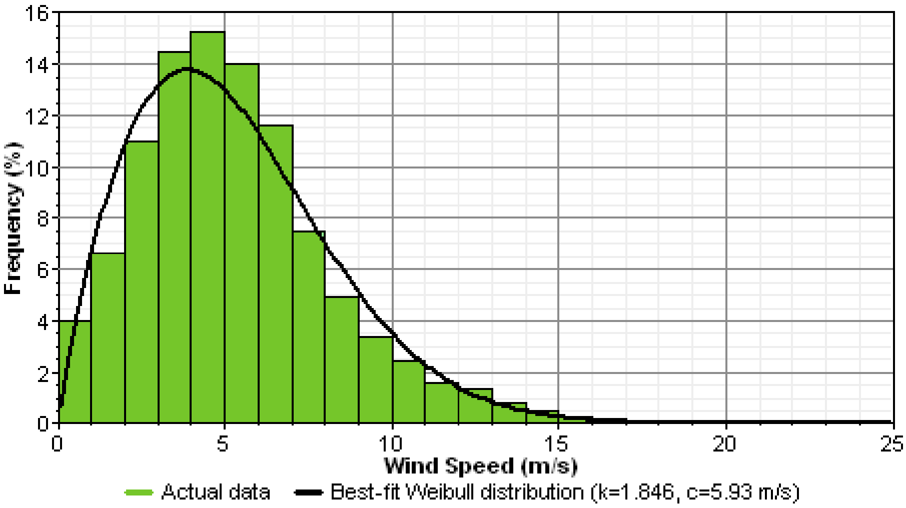
$$\bar{U} = c\boldsymbol{\Gamma}\left(\frac{\mathbf{1}}{\boldsymbol{k}} + \mathbf{1}\right)$$

where $\bar{U}$ is the long-term average wind speed and Γ is the gamma function.

The Weibull *k* value reflects the breadth of the distribution; the broader the distribution, the lower the value of the Weibull *k*. The graph below shows several Weibull distributions, all with an average wind speed of 7 m/s, but with the Weibull *k* value varying from 1.5 to 3.5.



The Weibull distribution often fits measured wind speed distributions well. The graph below shows a measured wind speed distribution along with the best-fit Weibull distribution:



Windographer uses the maximum likelihood algorithm to fit a Weibull distribution to a measured wind speed distribution.

Source: Tom Lambert
Contact: support@mistaya.ca
Last modified: February 24, 2008

Least Square Methodology for Determining the Shape and Scale Factors

We can use a linear least squares algorithm to fit a Weibull distribution to measured wind speed data, but first we need to do some algebra. We will start with the definition of the cumulative distribution function of the Weibull distribution:

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^k\right]$$

We can rearrange this to give:

$$-\ln[1 - F(U)] = \left(\frac{U}{c}\right)^k$$

And using the rule ln(1/A) = - lnA, we can write:

$$\ln\left[\frac{1}{1-F(U)}\right]=\left(\frac{U}{c}\right)^k$$

Taking the natural logarithm of both sides gives us:

$$\ln\left\{\ln\left[\frac{1}{1-F(U)}\right]\right\}=k\ln\left(\frac{U}{c}\right)$$

And using the rule ln(A/B) = lnA - lnB, we can write:

$$\ln\left\{\ln\left[\frac{1}{1-F(U)}\right]\right\}=k\ln U-k\ln c$$

This equation is now in the general slope-intercept form: $y=mx+b$. Therefore, if we were to plot ln*U* on the *x*-axis and ln{ln[1/(1-F(*U*))]} on the *y*-axis, we would expect a straight line with slope equal to *k* and intercept equal to -*k* ln*c*.

Therefore, to find the best-fit Weibull distribution according to the least squares algorithm, Windographer calculates ln*U* and ln{ln[1/(1-F(*U*))]} for every data point, then puts those values into a linear least squares solver to calculate the slope and intercept of the line of best fit. It then sets *k* equal to the slope of that line, and *c* equal to exp(-intercept/slope).

Source: Linda Sloka

Contact: **support@mistaya.ca**

Last modified: February 24, 2009

The Maximum Likelihood Methodology for Determining the Shape and Scale Factors

The maximum likelihood method (**Stevens and Smulders, 1979**) fits a Weibull distribution to a set of measured wind speeds. This method employs the following equation to calculate, in an iterative fashion, the Weibull *k* parameter:

$$k = \left(\frac{\sum_{i=1}^{N} U_i^k \ln(U_i)}{\sum_{i=1}^{N} U_i^k} - \frac{\sum_{i=1}^{N} \ln(U_i)}{N} \right)^{-1}$$

where U_i is the wind speed in time step i, and N is the number of time steps. Once the shape parameter k has been found, the following equation gives the value of the scale parameter c:

$$c = \left(\frac{\sum_{i=1}^{N} U_i^k}{N} \right)^{\frac{1}{k}}$$

Source: Tom Lambert

Contact: **support@mistaya.ca**

Last modified: February 24, 2009

The Wind Atlas Analysis and Application Programme (WAsP) Methodology for Determining the Shape and Scale Factors

The WAsP program has defined a requirement for fitting the Weibull distribution to measured wind speed data. The WAsP algorithm does not attempt to directly fit the measured frequency histogram, but rather requires that:

1. The power density of the fitted Weibull distribution is equal to that of the observed distribution.

2. The proportion of values above the mean is the same for the fitted Weibull distribution as for the observed distribution.

Let's deal first with requirement number 2. We begin by defining a symbol *X* to represent the proportion of the observed wind speeds that exceed the mean wind speed. The cumulative distribution function F(*U*) gives the proportion of values that are less than *U*, so 1-F(*U*) is the proportion of values that exceed *U*. We can therefore write requirement number 2 as follows:

$$X = 1 - F(\overline{U})$$

The cumulative distribution function of the Weibull distribution is given by the following equation:

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^k\right]$$

Since that equation holds for any wind speed *U*, it holds for the mean wind speed. We can substitute and rearrange to get:

$$1 - F(\overline{U}) = \exp\left[-\left(\frac{\overline{U}}{c}\right)^k\right]$$

The following equation gives the mean of the Weibull distribution:

$$\overline{U} = c\Gamma\left(\frac{1}{k}+1\right)$$

We can substitute that into the earlier equation to get:

$$1-F(\overline{U}) = \exp\left[-\left(\frac{c\Gamma\left(\frac{1}{k}+1\right)}{c}\right)^{k}\right] = \exp\left[-\Gamma\left(\frac{1}{k}+1\right)^{k}\right]$$

Now we can write requirement number 2 as follows:

$$X = \exp\left[-\Gamma\left(\frac{1}{k}+1\right)^{k}\right]$$

And taking the natural logarithm of both sides gives:

$$-\ln X = \Gamma\left(\frac{1}{k}+1\right)^{k} \qquad (1)$$

In performing the WAsP algorithm to fit the Weibull distribution, Windographer first calculates *X*, then solves the above equation iteratively, using the Brent method, to find the *k* parameter.

Requirement number 1 allows us to calculate the *c* parameter. To see how, we need to start with the equation that gives the mean wind power density (WPD) of the Weibull distribution, assuming constant air density:

$$WPD = \frac{1}{2}\rho\, c^{3}\, \Gamma\left(\frac{3}{k}+1\right)$$

We can also write an equation for the mean power density of the observed wind speeds:

$$WPD = \frac{1}{2N}\rho \sum_{N} U_i^3$$

Requirement number 1 says that these must be equal, so we can write:

$$c^{3}\Gamma\left(\frac{3}{k}+1\right) = \frac{1}{N}\sum_{N} U_i^3$$

Solving this for *c* gives us:

$$c = \sqrt[3]{\frac{\sum_{N} U_i^3}{N\Gamma\left(\frac{3}{k}+1\right)}} \qquad (2)$$

So when implementing the WAsP algorithm, Windographer uses equation 1 to calculate *k*, then equation 2 to calculate *c*.

Source: Linda Sloka

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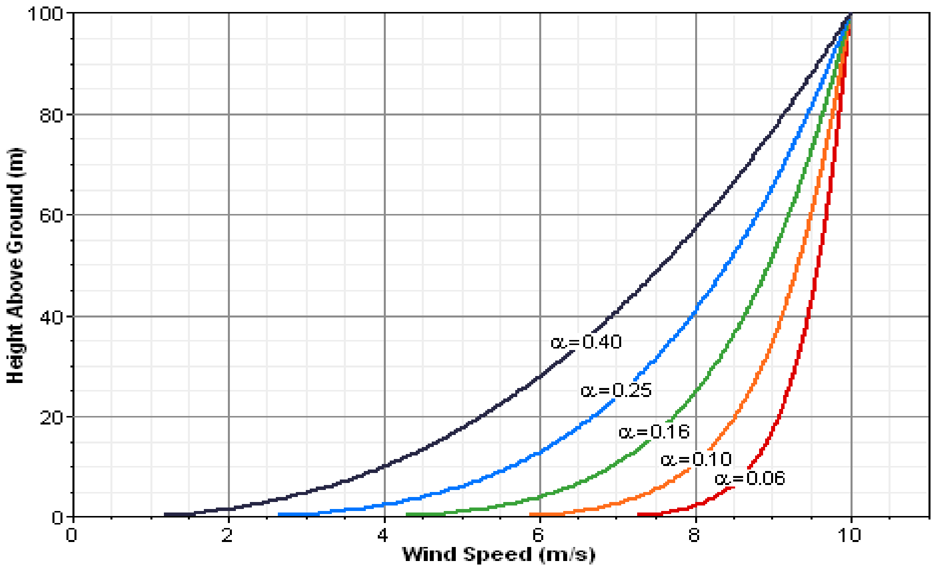
The Power Law Exponent

The power law exponent (sometimes called the power law coefficient) is a number that characterizes the wind shear, which is the change in wind speed with height above ground. The **power law** uses the power law exponent as a parameter. The graph below shows the effect of the power law exponent on the wind shear profile predicted by the power law. Each line on the graph corresponds to a different power law exponent, indicated in the graph with the symbol 'α'. In all cases, the wind speed is 10 m/s at 100m above ground. The wind speed at lower heights decreases with increasing power law exponent.



For data sets that contain wind speed data for two or more different heights above ground, Windographer calculates the power law exponent from the observed wind shear profile. To do so, Windographer solves for the value of the power law exponent that causes the power law profile to most closely fit the measured wind shear profile.

Note: Windographer can calculate the wind shear only if the data set contains two or more wind speed sensors at different heights. For data sets that contain wind speed data from only one height above ground, Windographer simply sets the power law exponent equal to the default value of 0.14.

The shape of the wind shear profile typically depends on several factors, most notably the roughness of the surrounding terrain and the stability of the atmosphere. Since the atmospheric stability changes with season, time of day, and meteorological conditions, the power law exponent also tends to change in time. The value of the power law exponent that Windographer displays on the Summary tab is based on the overall wind shear profile, meaning the wind shear profile that Windographer calculates from the entire data set. But Windographer also calculates the wind shear profile and corresponding power law exponent for each month of the year, each hour of the day, each wind direction sector, and each individual time step.

Source: Tom Lambert
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